Interim Report on Sodium Plugging Test

Global Nuclear Energy Partnership

Prepared for
U.S. Department of Energy
Campaign or Program

D. Cho, Y. Momozaki,
D. Kilsdonk, D. Engel,
R. Haglund, C. Reed
M. Farmer, and C. Grandy

April 30, 2008
GNEP-ANL-AFCI-232

Prepared by:

Principal Investigator: 4-30-08

Dae Cho Date

Principal Investigator: for 4-30-08

Yoichi Momozaki Date

Reviewed by:

Work Package Manager : 4/30/08

Christopher Grandy Date

WBS Level 4 Manager: 4/30/08

Christopher Grandy Date

Approved by:

WBS Level 3 Manager 4/30/08

Robert Hill Date

SUMMARY

To investigate the possible plugging of narrow flow channels due to an impurity (e.g. oxides) present in flowing sodium, a sodium-loop test apparatus has been constructed and is presently operational at ANL. This report summarizes the progress made since the construction of the apparatus and describes details of extensive operational experience. Based on the operational experience to date, it is believed that the objective of demonstrating no plugging with clean sodium (i.e. the sodium temperature being well above the impurity saturation temperature) has largely been achieved.

CONTENTS

FIGURES

ACRONYMS

ABR	Advanced Burner Reactor
ANL	Argonne National Laboratory
DC	Direct Current
EM	Electro Magnetic
ID	Inner Diameter
OD	Outer Diameter
PCHE	Printed Circuit Heat Exchanger
TC	Thermocouple

REACTOR CAMPAIGN/INTERIM REPORT ON SODIUM PLUGGING TEST

1. INTRODUCTION

In the ABR concept employing the supercritical CO2 Brayton cycle power conversion technology, a compact heat exchanger known as the printed circuit heat exchanger (PCHE) is being considered for the sodium-to-CO2 heat exchanger. Each PCHE is essentially a monolithic block of stainless steel, containing embedded narrow flow channels. Plugging of these narrow flow channels due to an impurity (e.g. oxides) present in the sodium is a possibility if the sodium should become supersaturated with the impurity. Under normal operating conditions with a properly functioning cold trap, no plugging would be expected. However, in certain transients, possibly coupled with offnormal occurrences (e.g. air ingress into the system or cold trap malfunction), the impurity dissolved in the sodium could precipitate and deposit on the walls of the flow channels, eventually leading to the channel plugging. Experimental data is needed to assess this plugging question for the optimum design of the PCHE sodium-CO2 heat exchanger. Accordingly, a test apparatus including a sodium loop has been constructed in order to provide baseline data for the evaluation of potential sodium plugging in PCHE flow channels. The design and construction of the test apparatus was documented in a report issued in FY 2007[1]. This report summarizes the progress made since the issuance of the apparatus report. For completeness, however, the previous description of the apparatus has been updated and included in this report.

2. Objectives

Two specific objectives are:

1. To demonstrate that for the PCHE flow channel sizes being considered for the sodium-to-CO2 heat exchanger, no plugging occurs if the sodium temperature is well above the impurity (i.e. oxides) saturation temperature.
2. To collect experimental data which will be used to model the plugging behavior as a function of the channel size as well as the amount of impurity supersaturation.

As will be discussed in Section 6 of this report, it is believed that the first objective has largely been achieved during this first phase of FY08 work. The second objective will be addressed in the second phase and will be discussed in the final report.

3. Apparatus

As shown schematically in Figure 1, the apparatus consists of a main sodium loop including three test sections, a bypass sodium loop including a cold trap/economizer assembly, and an auxiliary system comprising Argon and vacuum lines. The main loop as well as the bypass loop is constructed from ½ - inch OD, 0.049-inch thick, type 316 stainless steel tubing. Other major components include three EM flow controllers (one each for the three test sections), two EM pumps (one for the main loop and one for the bypass loop), five EM flow meters, and expansion and dump tanks. The apparatus is located in Building 370, Room C-1.

The entire apparatus except the auxiliary system is placed over a stainless steel drip pan (2540 mm x 1422 mm x 51 mm). The sodium loop system is about 1.8 m tall and is heated by a number of ceramic band heaters. An assembly drawing of the apparatus is shown in Figures 2 and 3.

3.1 Test Sections

The test sections simulate PCHE flow channels having three different channel sizes. Test Sections #1 has 9 semi-circle, 2-mm diameter flow channels. Test section #2 has 4 semi-circle, 4-mm diameter flow channels. Test section #3 has 3 semi-circle, 6-mm diameter flow channels. The three test sections have the same flow channel length, namely 780 mm, and they are installed in parallel in the main loop. The cross-sections of the three test sections are shown in Figure 3. As can be seen, the flow channels are formed in 0.25-inch thick 304 stainless steel plates which are welded to 304 stainless steel cover plates. The test section parameters are based on the PCHE design calculations performed by Anton Moisseytsev at ANL[2].

The test sections are installed using VCR Swagelok fittings and elbows so as to facilitate their removal. Thus, test sections for a variety of investigations may be designed and installed. The only limitation would be the length of the test section, which is limited to 780 mm.

3.2 Expansion Tank

The expansion tank is constructed from 6-inch, schedule 40, type 304 stainless steel pipe and is connected to the main sodium line at the highest point of the loop. The tank has penetrations for a level probe, thermocouple and Argon/vacuum line. The volume of the expansion tank is 5.4 liters. Two drawings of the expansion tank are shown in Figures 4 (as built) and 5 (with connections). The expansion tank was manufactured by Buckeye Fabricating in Springboro, Ohio.

3.3 Dump Tank

The dump tank is constructed from 8-inch, schedule 40, type 304 stainless steel pipe and is located below the sodium loop. A 3-inch flanged fill port is provided for sodium loading into the dump tank. The blind flange for the fill port has a penetration for an Argon/vacuum line. The dump tank has penetrations for a level probe, thermocouple, sodium transfer line, and sodium dump line. The sodium dump line is connected to the loop, but it is isolated from the loop by a dump valve during normal loop operations. The volume of the dump tank is 12 liters. Two drawings of the dump tank are shown in Figures 6 (as built) and 7 (with connections). The dump tank was manufactured by Buckeye Fabricating in Springboro, Ohio.

3.4 EM Pumps

Two identical round-duct, direct-current (DC), electro-magnetic (EM) pumps were designed and assembled at ANL. Figure 8 shows the design of the EM pump while Figures 9 and 10 show the EM pumps mounted in the bypass loop for the cold trap and in the main loop for the test sections, respectively.

3.5 EM Flow Controllers

Three identical round-duct, direct-current (DC), electro-magnetic (EM) flow controllers were designed and assembled at ANL. The design of these EM flow controllers is essentially the same as that of the EM pumps, and they increase or decrease the sodium flow rate, depending on the polarity of the electric current. Figure 11 shows the design of the EM flow controllers while Figure 12 shows an EM flow controller mounted in the main loop for one of the three test sections.

3.6 EM Flow Meters

Five identical electro-magnetic (EM) flow meters were designed and assembled at ANL. These EM flow meters are installed in the various parts of the loop system, as indicated in Figure 1. Figure 13 shows the design of the EM flow meters while Figure 14 shows an EM flow meter mounted in the loop system.

3.7 Cold Trap/Economizer Assembly

The cold trap/economizer assembly is shown in Figure 15. The cold trap is a section of stainless steel pipe (3-inch, schedule 40, type 304) which is packed with stainless steel mesh, providing a large surface area. The economizer is a tube-in-tube type heat exchanger with the inner tube being the ½ - inch stainless steel loop tubing. The outer boundary of the economizer is constructed from 1 ½ inch, schedule 40, type 304 stainless steel pipe. The loop sodium is partially cooled as it flows through the economizer. The partially cooled sodium enters the cold trap and is further cooled there. Any oxide which precipitates as a result of the cooling process deposits in the packed section of the cold trap.

The cold trap temperature will be controlled by the clam-shell ceramic heaters surrounding the cold trap as well as an air blower. The air blower will supply air flows through the gap between the heaters and the outer surface of the cold trap. The cold trap temperature will be monitored using a 5-junction, type K, thermocouple probe, which is shown in Figure 16.

3.8 Argon and Vacuum Lines

The Argon and vacuum lines are connected to the expansion and dump tanks. The Argon line provides Argon flows from a supply cylinder while the vacuum line is used to evacuate the loop system. A part of the Argon line including the supply cylinder is located outside the Room C-1 confinement.

Two in-line stainless steel filters installed on the Argon/vacuum lines serve as sodium vapor traps. An air-driven valve is located between the two vapor traps. This valve is normally open, but closed during the transfer of molten sodium from the dump tank to the loop system.

3.9 Heaters

All heaters are ceramic band heaters of various sizes. These heaters were installed in nine different zones of the apparatus. These nine zones are: (1) expansion tank, (2) upper half of loop tubing, (3) test section # 1, (4) test section #2, (5) test section #3, (6) lower half of loop tubing, (7) dump tank, (8) economizer, and (9) cold trap. The heaters for each of the nine zones are wired in such a way that the power input is optimum for the intended operation of the apparatus. The wiring involved a combination of parallel and series connections.

Each heating zone is connected to the solid state heater power controller. The heater power controller is simultaneously controlled by two temperature controllers. One controller is to accurately control the temperature and another is to turn off the power to the heater when the temperature exceeds the set point. This latter heater contoller is to provide an extra overtemperature protection to the heater control system. These temperature controllers require thermocouple (TC) inputs to them. These TC systems are described next.

3.10 Thermocouples

The temperatures of the various parts of the apparatus are monitored by Type K thermocouples (TCs). There are two different TC systems in the apparatus. One is for recording temperature data and another is for monitoring temperature to control the heater system to operate the apparatus at desired operating temperatures. For recording purposes, 39 TCs are attached to the outside surfaces of the various parts, and a 5-junction TC probe is embedded in the cold trap. The locations of these recording TCs are shown in Figure 17. These TCs are planned to be connected to a data logger and collected data are subsequently sent to the computer for display and storage.

For temperature controlling purposes, 11 TC bundles are employed. Each TC bundle contains 3 Type-K TCs. The first of the 3 TCs is to provide an input to a temperature controller, the second is to provide separate input to another temperature controller for independent over temperature protection, and the third is a spare. There are 2 spare TC bundles in the apparatus for contingencies.

3.11 Sodium Melter

Sodium was supplied in a can containing a one-pound dry sodium slug which was a square block (7 cm x 7cm x 10cm). This sodium slug was loaded into a melter which was attached to the top port of the dump tank. The melter was made from 18-inch long, 4-inch diameter stainless steel tubing with a ConFlat flange on one end. An assembly drawing of the melter attached to the top port of the dump tank is shown in Figure 18.

3.12 Impurity Removal from Loop System

Impurities such as moisture and oil residue were removed from the loop system by simultaneously evacuating and heating the system up to approximately 400°C for an extended period of time.

4. Sodium Loading

A mass of sodium was loaded into the dump tank. The total mass of sodium placed in the dump tank was 6.7 kg.

The sodium was supplied in a can containing a reagent grade, one-pound dry sodium slug which was a square block having dimensions of 7 cm x 7 cm x 10 cm. The sodium slug was first loaded into a melter which was attached to the top port of the dump tank. (Figure 19 shows a sodium slug placed in the melter.) This sodium loading was performed employing a glove bag attached to the top flange of the melter. The glove bag as well as the melter and dump tank assembly was continually purged with Argon during the loading operation. After loading up to 4 sodium slugs, the top cover of the melter was reattached and the glove bag was removed. Then the melter and dump tank assembly was heated to above the melting point of sodium, allowing the sodium to melt and drain into the dump tank. (Figure 20 shows the inside of the melter after the sodium melt draining into the dump tank.) This loading/melting procedure was repeated until all 14 slugs of sodium were placed in the dump tank.

5. Sodium Transfer and Shakedown Testing

Prior to sodium transfer from the dump tank to the loop, the entire loop was fully evacuated while the dump tank, which was under Argon cover gas, was isolated from the loop by a spring-loaded dump valve. The sodium in the dump tank was melted at a temperature in the range of 150-200°C and was transferred to the bypass loop (with the test sections isolated) by opening the dump valve.

Following the sodium transfer to the loop, shakedown testing started. The shakedown testing involved molten sodium moving through the bypass loop containing the cold trap. The two primary objectives of the testing were to: 1) check out the operation of the EM pumps and flow meters and 2) examine the workings of the cold trap control system while cleaning up the sodium.

The EM pump for the cold trap was tested. Initially, the pump did not respond to the power input to the EM device. This failure of the pump to start was judged to be due to the poor wetting of the flow duct (i.e. ½-inch stainless steel tubing) by the sodium. Accordingly, the loop temperature was increased to 400-425°C , and after a waiting period, the sodium was partially drained in order to cause movement of the sodium in the flow duct. This maneuvering worked. The pump started to run. Thereupon, the loop temperature was lowered to approximately 200°C.

After 3 days of uninterrupted running, the loop temperature was increased to 250°C. Sometime after this temperature increase, a sharp metallic noise similar to engine knock began to be heard, a few times per second. The noise appeared to be coming from a region above the pump. It was believed that the noise was caused by the collapse of cavitation bubbles, since the loop operation was being conducted under vacuum. It was then decided to introduce Argon gas to the expansion tank. When the loop pressure was brought to about one tenth of atmospheric (1.5 psia), the noise disappeared.

Toward the end of the shakedown testing, the loop was evacuated again, and the three test sections were filled with molten sodium by opening the test section isolation valves while maintaining the bypass flow through the cold trap. The main pump was then started, resulting in sodium flows through all three test sections (2-mm, 4-mm and 6-mm ID channels). The test section temperatures were about 300° and the cold trap temperature mostly was in the range of 130 to 140°C.

6. Demonstration Testing

Demonstration testing began on December 7, 2007 as the shakedown testing ended. During most of the testing, basically two modes of stable operation were established. In the first mode, both the main and bypass pumps were on, but the flow controllers for the three test sections were off. There were sodium flows through all three test sections (2-mm, 4-mm and 6-mm flow channels) with the flow rate increasing with increasing channel diameter. In the second mode, the flow controller power inputs were adjusted in such a way that the flow rates of the three test sections were about equal. The test section temperatures typically were about 300°C and the cold trap temperature was in the range of 120-140°C. Based on the operational experience thus far, it appears that the objective of the testing, namely demonstrating no channel plugging with clean sodium, has largely been achieved.

The sodium loop was operated for almost 150 full days for the demonstration testing. During this operating time, sodium flowed continuously through all three test sections, although the flow rates varied, depending on the power inputs to the pumps and flow controllers. As indicated above, the test section temperatures (about 300°C) were well above the cold trap temperature (mostly in the range of 120-140°C). The impurity (i.e. oxide) saturation temperature depends on the oxygen content of the loop sodium, but it should not exceed the cold trap temperature. Thus, it is believed that the objective of demonstrating no channel plugging with clean sodium (i.e. the sodium temperature being well above the impurity saturation temperature) has largely been achieved.

6.1 Exploratory Testing

When the initial demonstration test run started on December 7, 2007, the loop operation was under vacuum. The test section temperatures were about 300°C and the cold trap temperature mostly was in the range of 130-140°C. The EM flow meter readings were taken manually, using a volt meter.[1] These flow meter readings taken (in mV) indicated that sodium was flowing through all three test sections (2-mm, 4-mm and 6-mm ID channels). During the following two weeks, there were no noticeable changes in the loop operation including the test sections flows.

Later in this test run, we were experiencing noise with attendant temperature fluctuations. It was thought that the noise (knocking sound) was caused by collapsing cavitation bubbles. The loop was opening under vacuum. It was decided to suppress the noise by adding a small Argon pressure to the expansion tank. When an Argon pressure less than 1 psia (more likely about ½ psia) was added, the noise disappeared. Then, it was found that there were no indications of flow through the test sections, no flow through any of the three test sections. The loop was evacuated again, but the test section flows were not restored. Eventually, activation of two of the test section flow controllers caused sodium to flow through the test sections. Apparently, there was no permanent plugging of the test section flow channels. This sequence of events was repeated later on when the LabView data acquisition system became available for monitoring flow rates. The flow record taken is shown in Figure 21.

Most of the later exploratory test runs involved adjusting the power inputs to the test section flow controllers in such a way that the flows through the three test sections were about equal. The flow record of such a test run is shown in Figure 22.

During the exploratory testing, a number of operational instabilities were observed. These included: various types of flow fluctuations, the most prominent being wild flow oscillations accompanied by noise, sudden transition of a stable state to unstable state involving flow fluctuations (an example is shown in Figure 23) and sudden transition of a stable state to a different stable state, often involving smaller flow rates through the test sections. When these instabilities occurred, a new state of stable operation was established by "rebooting" the loop, i.e. shutting down all EM pumps and flow controllers and then restarting the bypass pump for the cold trap followed by the main pump for the test sections.

6.2 Selected Test Runs at 1 psig

It is planned to conduct future tests for plugging data under Argon cover gas at 1 psig. To learn about the loop operational behavior at this pressure, a series of test runs were made. Information collected from these test runs are summarized here.

Depending on the power inputs to the EM pumps and flow controllers, the sodium flows through the test sections may either be in the direction of the main pump ("forward flow") or in the opposite direction ("backward flow"). When the main pump was on with all three flow

[1] The LabView data acquisition system was installed about a month later

controllers off, the test section flows were forward. When the main pump was off with the flow controllers on, the test section flows were backward.

A few test runs were made with the main pump off. They all involved backward flows in the test sections. When the test section flow controllers were powered individually, the flow increased steadily with increasing power input up to about 90% of the maximum power and decreased steadily with decreasing power input down to zero power. All three test sections exhibited similar flow behavior, as shown in Figure 24-26. (In these figures the EM flow meter readings, mV, were plotted against the pump current, A.) However, when the three flow controllers were powered together, the resulting flow responses to the power inputs were complicated and were difficult to correlate with the power inputs.

Two test runs looking at the flow response to the power input to the cold trap pump were made. These runs were made with the test sections isolated and the main pump off. In the first run, the flow direction was forward with the polarity of the cold trap pump kept as originally assembled. Initially, the cold trap flow increased with increasing power input, but the flow increase stopped at a power input well below 50% of the maximum. When the power input was decreased down to zero, the flow steadily decreased to zero. This run was repeated twice, and the overall flow behavior was similar although the initial flow response was somewhat erratic and seemed to depend on the rate of increase of the power input. In the second run, the polarity of the cold trap pump was reversed, so the flow direction was reversed. The flow steadily increased with increasing power input up to about 90% of the maximum power. When the power input was decreased down to zero, the flow decreased steadily to zero, following the same path as taken by the flow response to increasing pump power. The flow responses to the power inputs in these two runs are shown Figure 27. (The first run is indicated by a black solid line while the second run is indicated by a red broken line.)

In the figures discussed above, the EM flowmeter readings were given in mV. Based on the flowmeter characteristics estimated theoretically, these mV readings were converted to volumetric flow rates given in m^3/s. The flow data for the second test run of the cold trap pump (indicated by a red broken line in Figure 27) was re-plotted in terms of volumetric flow rate (m^3/s) vs. pump current (A). This re-plotted data is shown in Figure 28, and may be used to estimate the pressure drop in conjunction with the theoretical pump characteristics. Such an estimate was made and is shown in Figure 29 as a broken curve, which is overlaid in a plot of the pump characteristics (i.e. pressure head vs. flow rate for given EM pump current).

A test run was made with the specific objective of testing the main pump. The cold trap pump as well as all three flow controllers for the test sections was off. It appeared that the flows were reaching a maximum at a pump power input less than 30% of the maximum power. The various flow responses to the power input are shown in Figure 30.

The test runs described above were made at a nominal loop temperature of 300°C while the cold trap temperature was in the range of 120-140°C. Additional test runs were made at higher nominal loop temperatures of 400 and 450°C while the cold trap temperature was mostly in the range of 200-220°C. (The test section temperatures were very close to the nominal loop temperature, but the temperatures of other parts of the loop varied somewhat.) By and large, it appeared that the window for stable operation was larger at the loop temperatures of 400 and 450°C than it was at 300°C. For example, in a test run involving the cold trap pump (with the test sections isolated and the main pump off), the forward flow exhibited instability at about 80% of the maximum pump power whereas in an earlier test at 300°C, similar instability occurred at about 40% of the maximum pump power. When the polarity of the pump was reversed, resulting in reverse (or backward) flow, stable flows were observed up to 90% of the maximum pump power, as was noticed earlier at the loop temperature of 300°C. The flow meter readings vs power current for both forward and reverse flows are shown in Figure 31. Figure 32 compares the flow rates estimated for the reverse flow at two different loop temperatures (300 and 450°C).

7. Preliminary Test Plans for Plugging Data

Currently, the oxygen content of the loop sodium is not known. Thus it is planned to obtain plugging data by proceeding in two stages.

In the first stage, a series of tests will be conducted to determine the test section temperature at which indications of test section plugging (e.g. flow reduction with time) occur. Initially, stable loop flows will be established with test section flows comparable to those being considered for a prototypical PCHE sodium /CO_2 heat exchanger, which are about $6x10^{-3}$ kg/s. In this initial test run, the test section temperature will be much higher than the cold trap temperature (e.g. test sections at 400°C and cold trap at 200°C). Then, the test section temperature will be reduced in steps, approaching the cold trap temperature. After each step of the temperature reduction, flow rate changes in each of the test sections will be carefully monitored. When a significant flow reduction is observed, the test section temperature will be increased so as to prevent complete plugging from occurring. Depending on the test results, the cold trap temperature may be adjusted.

If the results of the first-stage testing suggest that the oxygen content of the loop sodium is too low (i.e. the plugging temperature is too low) for meaningful plugging tests, a known amount of oxide will be added to the loop sodium. For example, the amount of oxide may be that which corresponds to the solubility of oxygen in sodium at 300°C, which is 142 ppm [3]. Assuming that the oxide is monoxide (Na_2O), the corresponding mass of oxide dissolved in the loop sodium will be 3.7 g. This mass of oxide may readily be added to the loop sodium via the expansion tank.

The second stage of testing will involve a systematic variation of the test section and cold trap temperatures without complete plugging. The effect of oxygen superstaturation on the plugging behavior will be quantified by conducting tests which involve test section temperatures lower than the cold trap temperature.

8. References

1. D. Cho, Y. Momozaki, D. Kilsdonk, R. Haglund, C. Reed and M. Farmer, “Apparatus for Sodium Plugging Test”, ANL-AFCI-191, Argonne National Laboratory, June 15, 2007.
2. A. Moisseytsev’s contribution in “Advanced Burner Test Reactor Preconceptual Design Report”, (Y.I. Chang, P.J. Finck and C. Grandy, Project Leaders), ANL-ABR-1 (ANL-AFCI-173), Argonne National Laboratory, September 5, 2006, pp. 91-96.
3. V. J. Rutkauskas, “Determination of the Solubility of Oxygen in Sodium by Vacuum Distillation”, LA-3879, UC-80, Reactor Technology TID-4500, Los Alamos Scientific Laboratory, July 15, 1968.

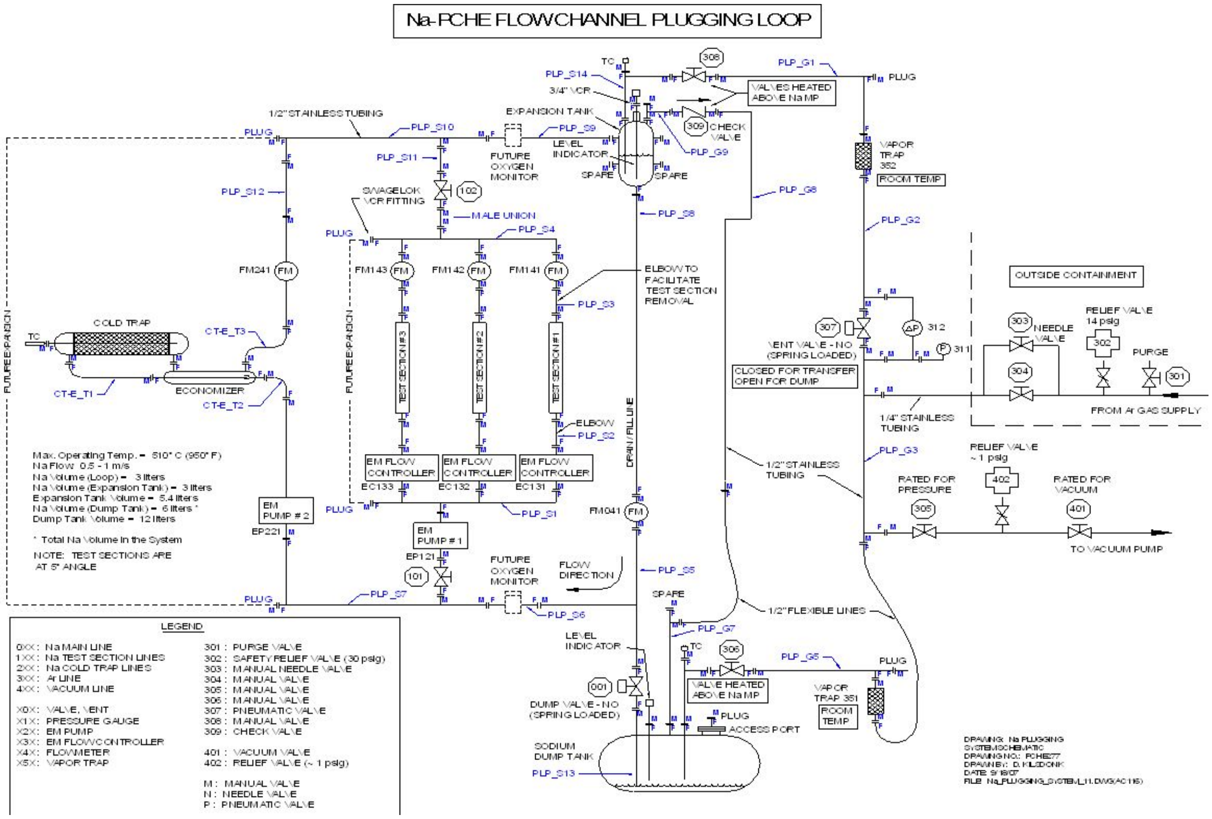

Figure 1 Apparatus Schematic

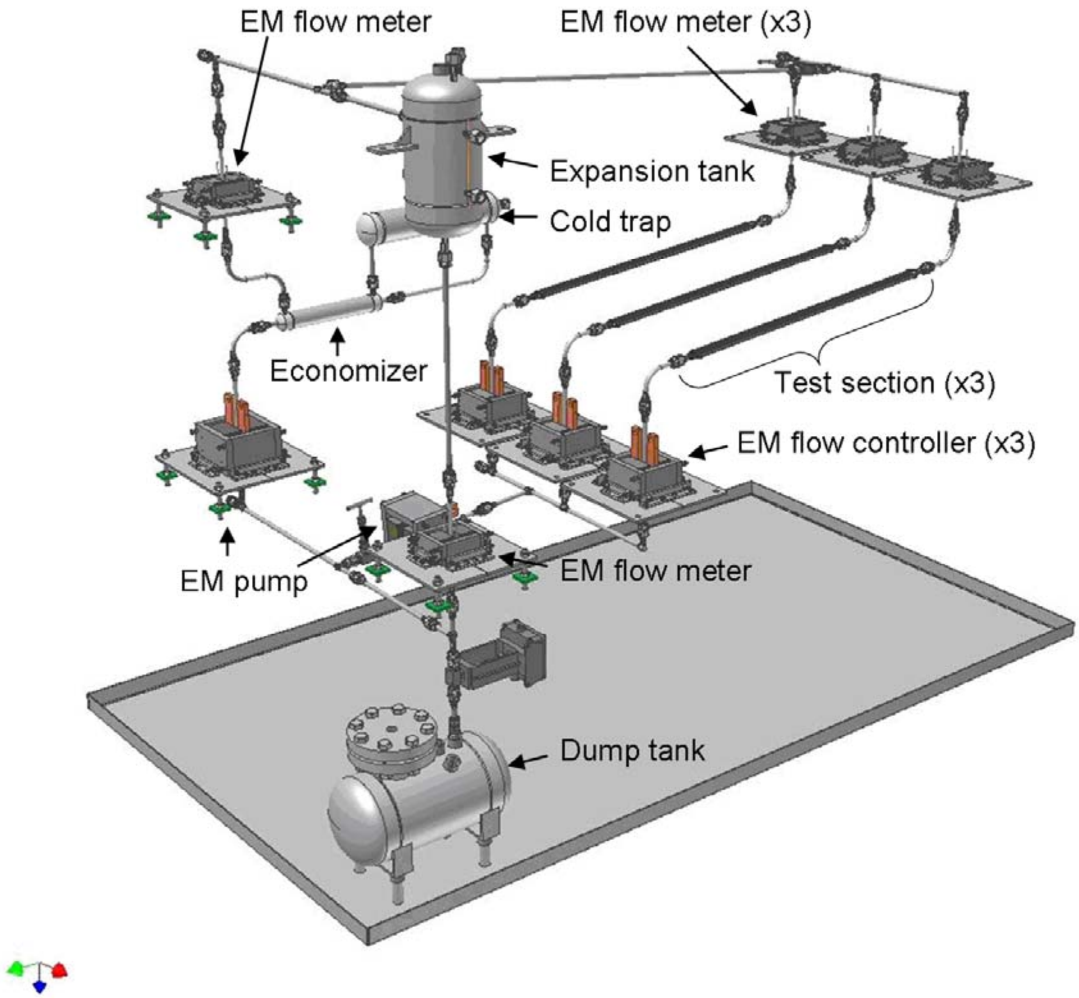

Figure 2 Apparatus Assembly Drawing

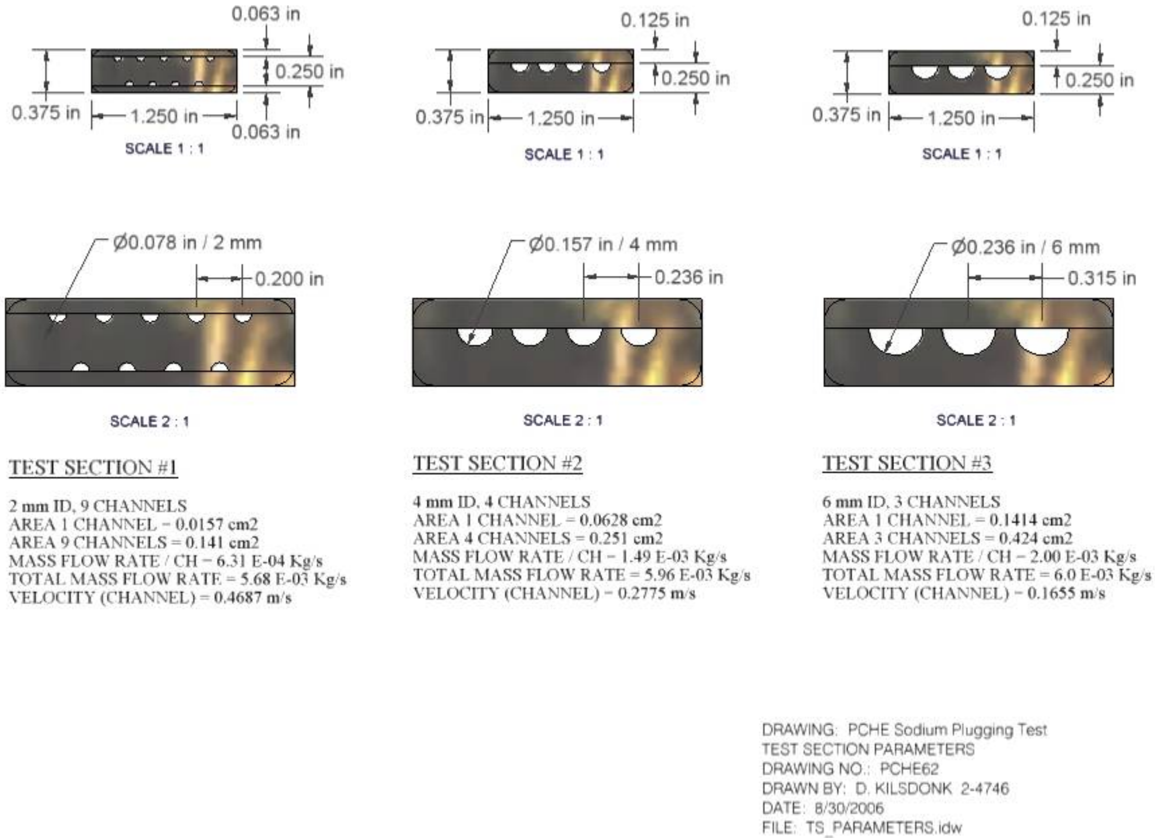

Figure 3 Cross Section of Three Test Sections

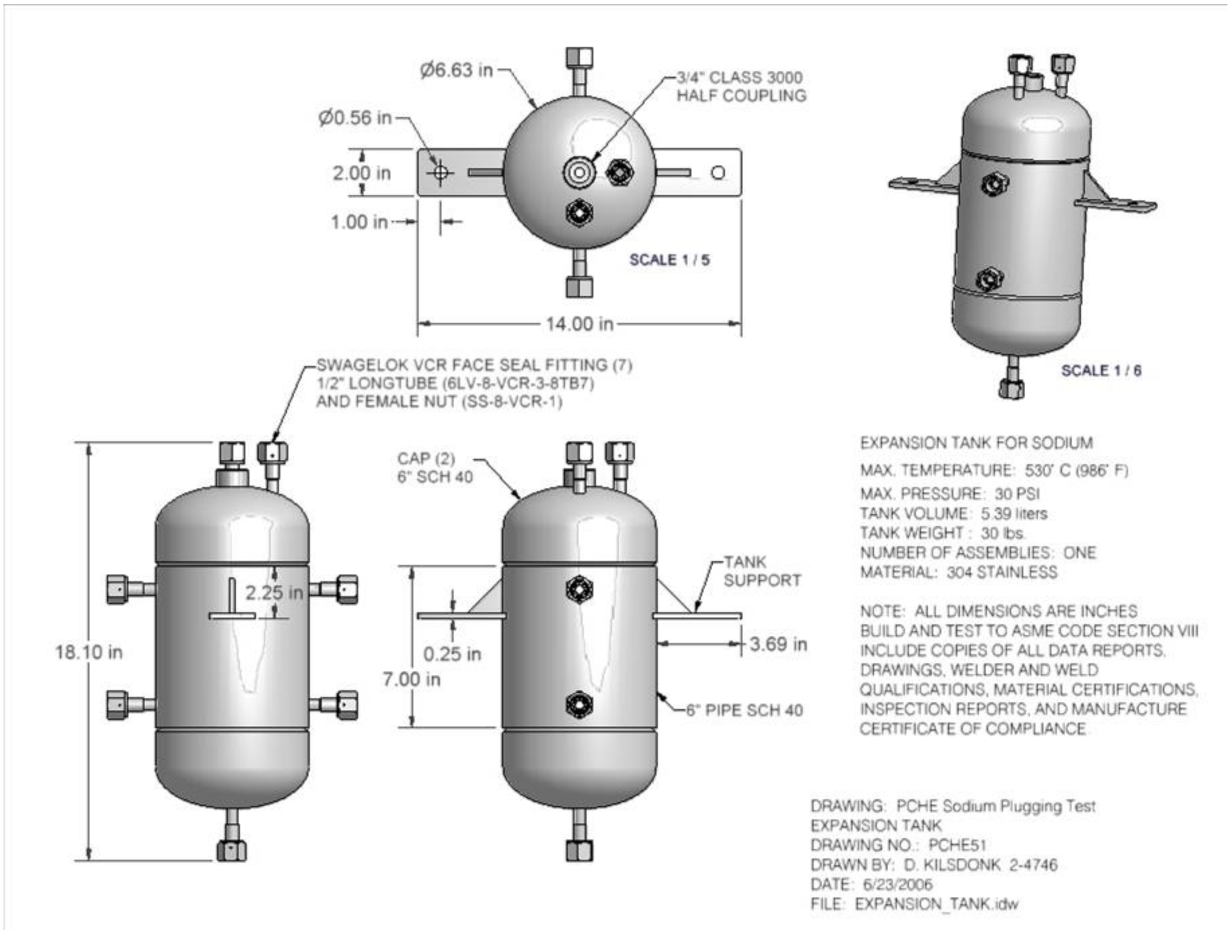

Figure 4 Expansion Tank As Built

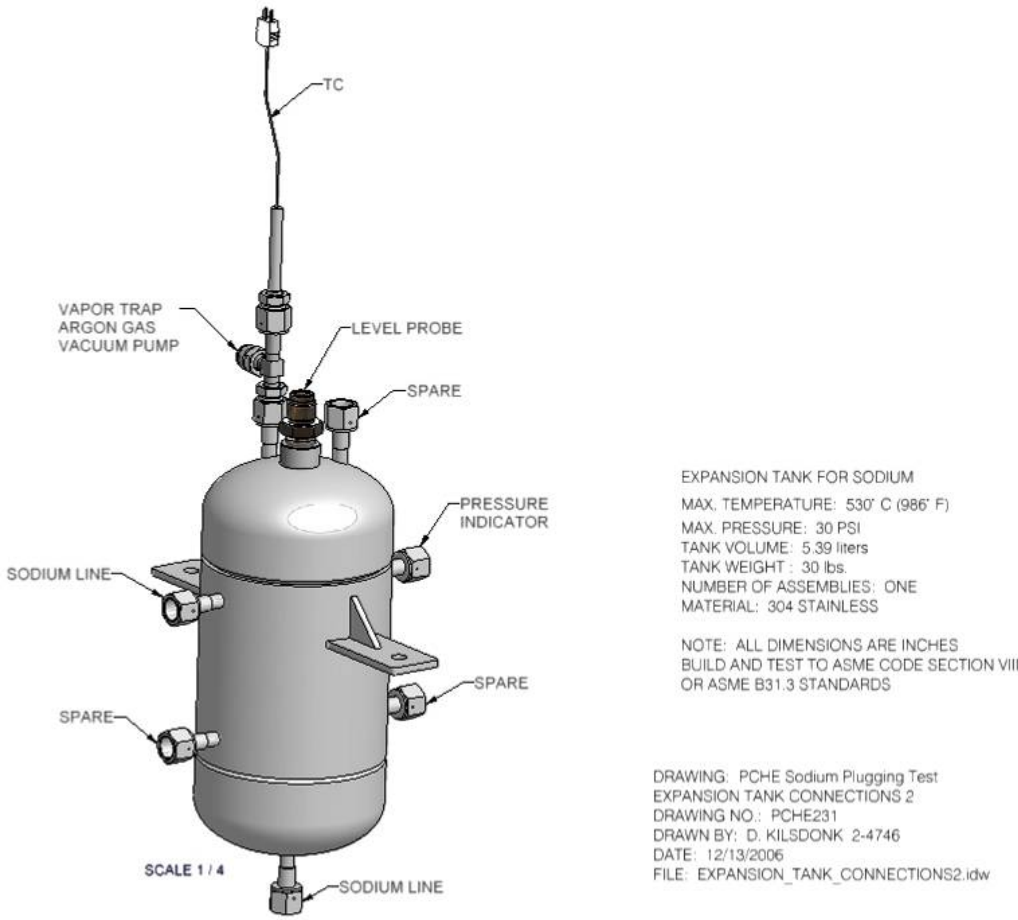

Figure 5 Expansion Tank with Connections

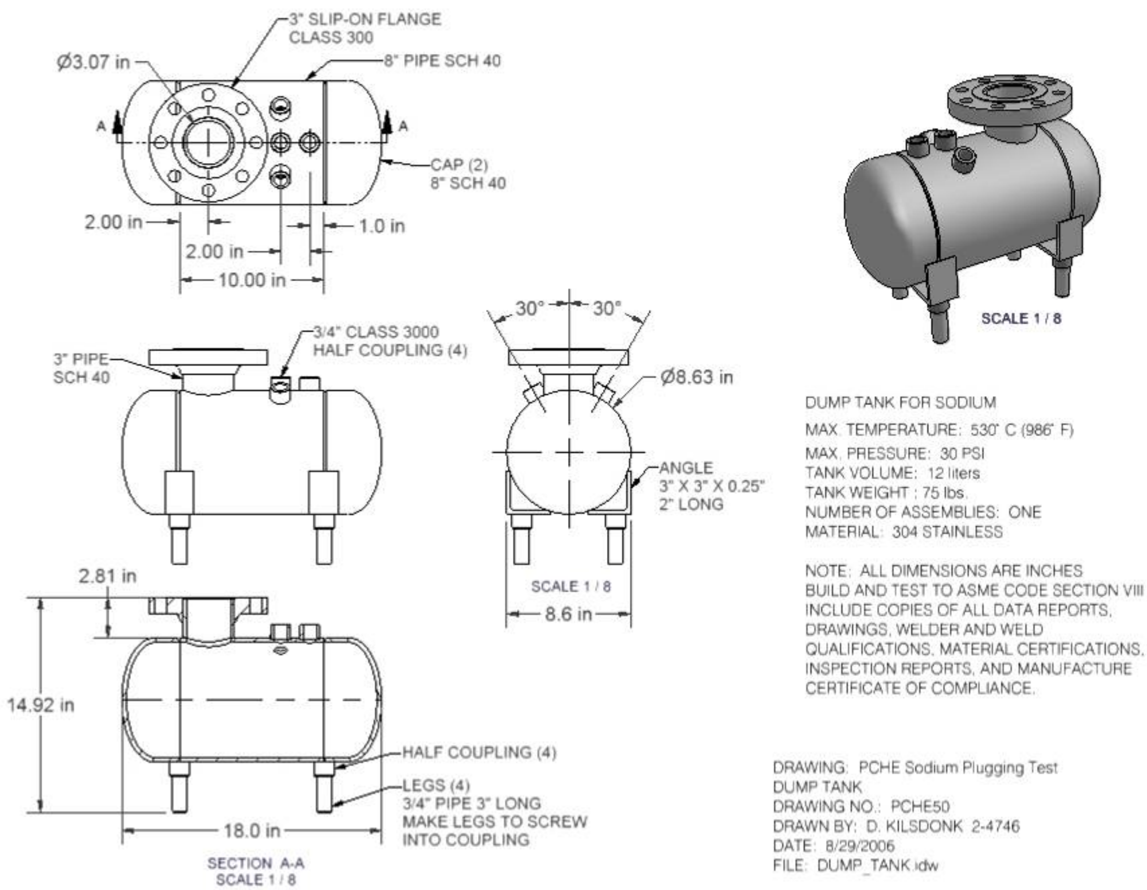

Figure 6 Dump Tank As Built

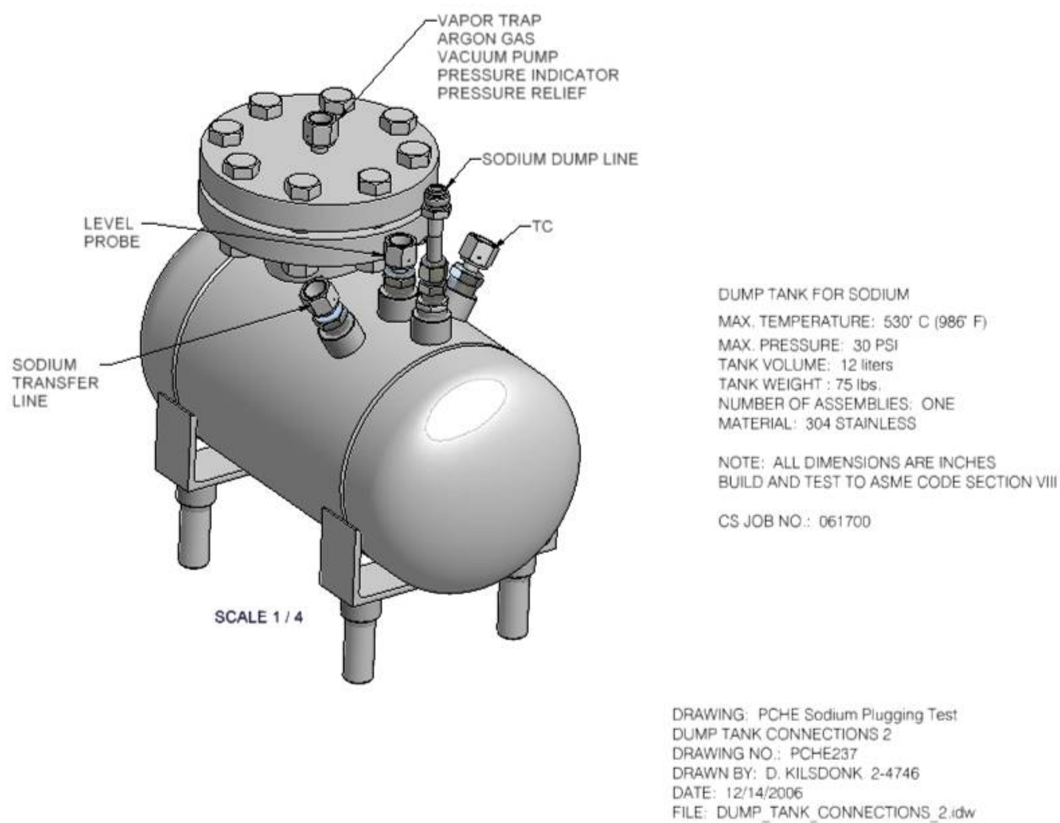

Figure 7 Dump Tank with Connections

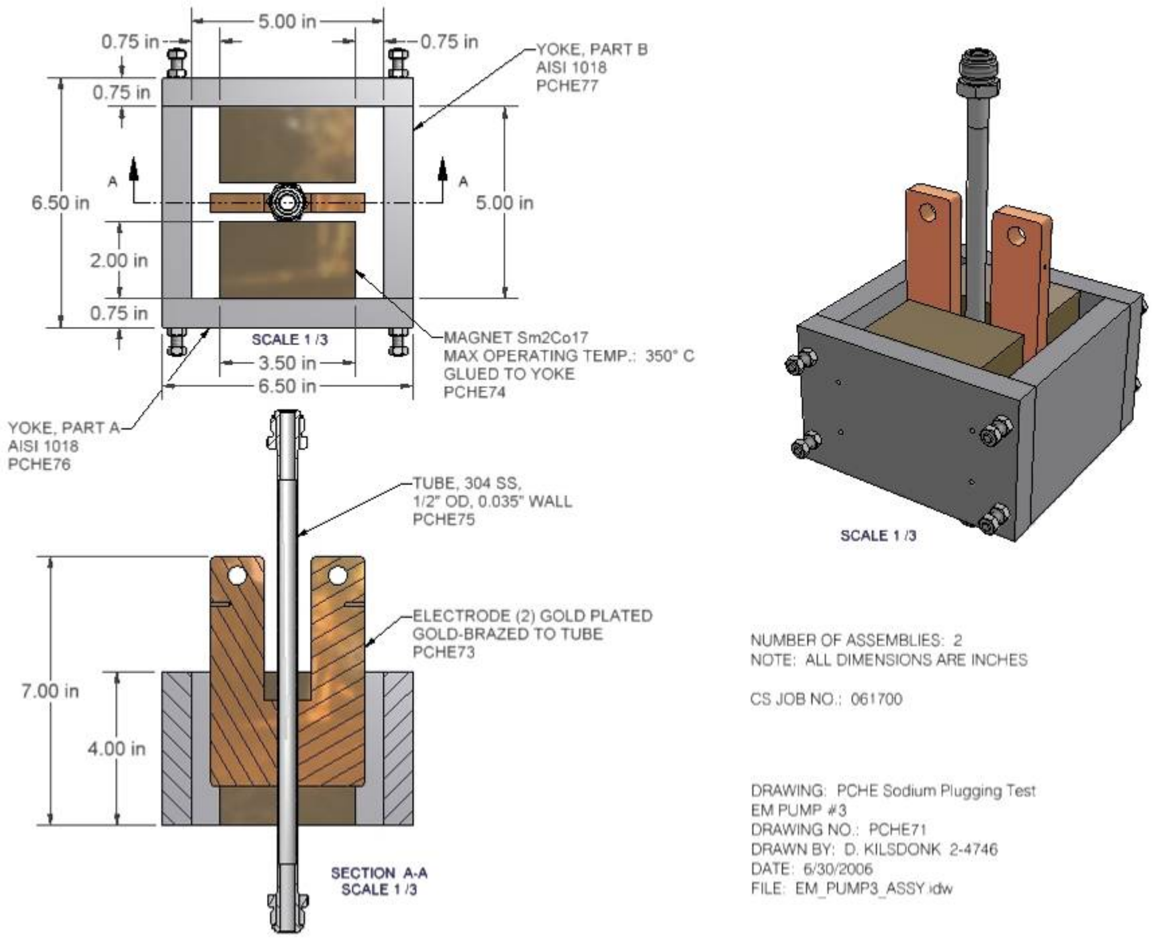

Figure 8 EM Pump Design

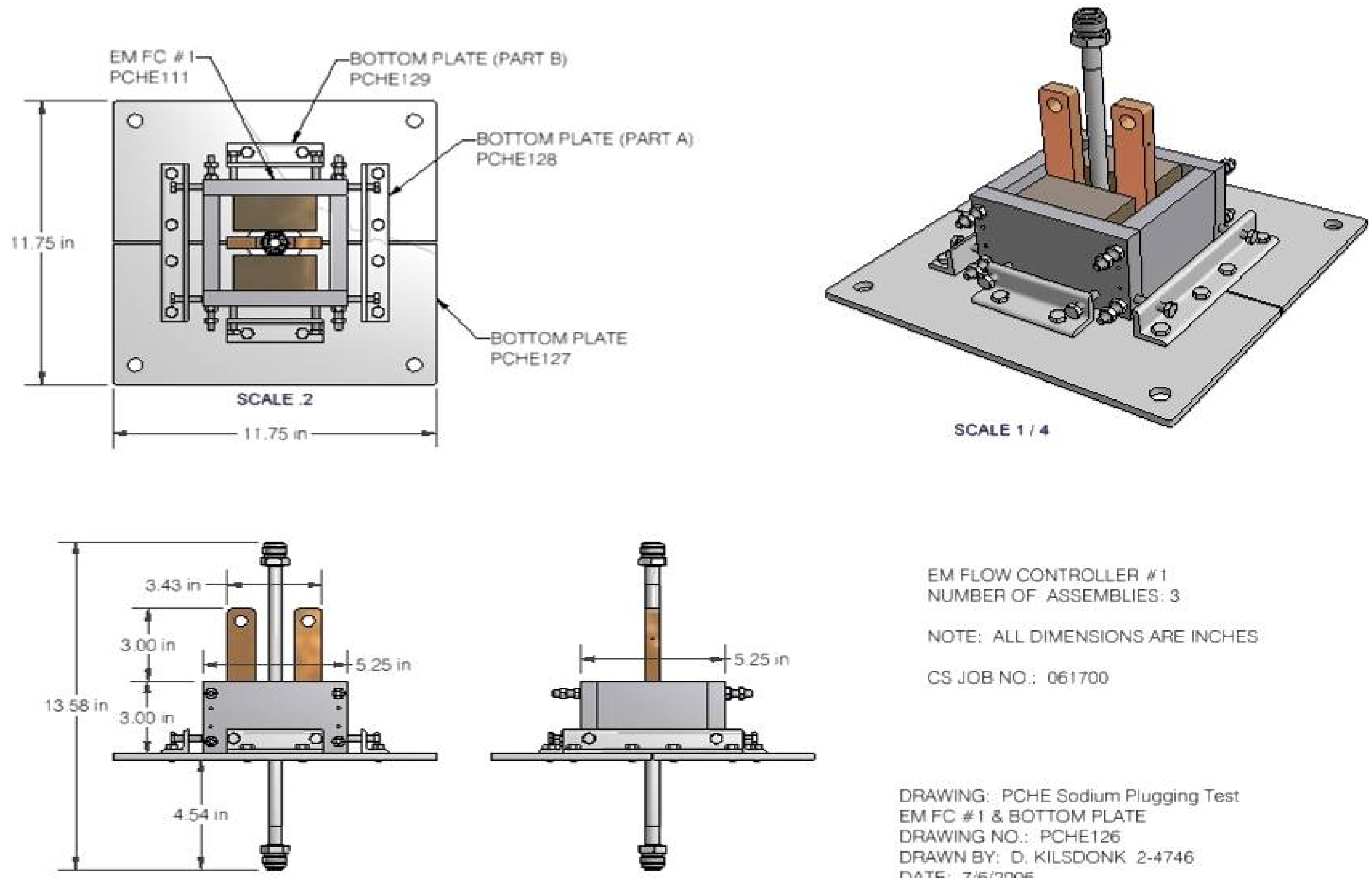

Figure 9 EM Pump Mounted for Cold Trap

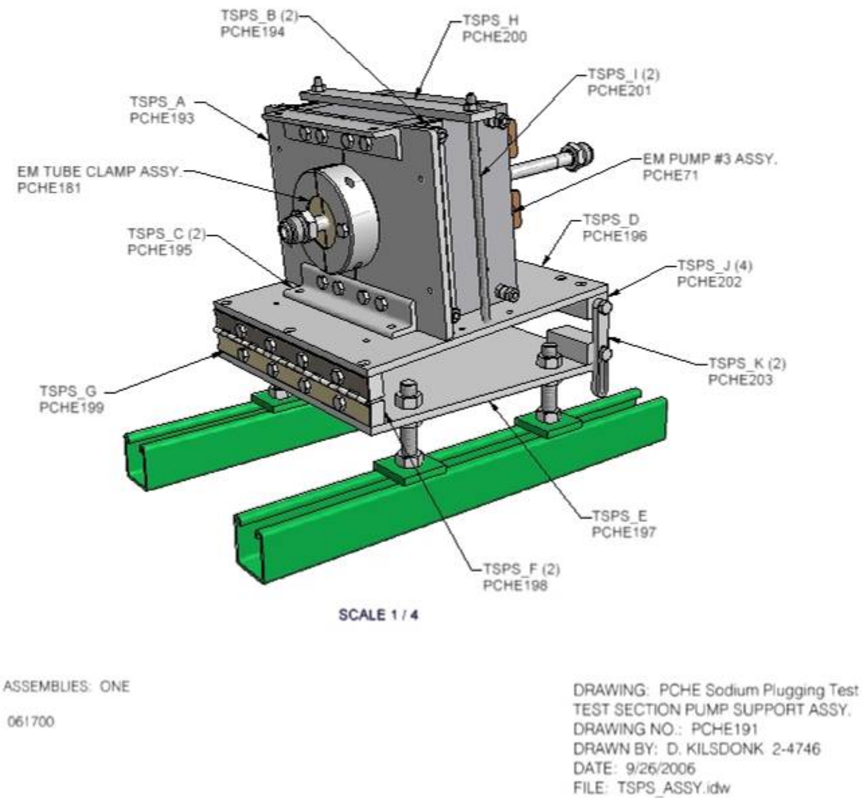

Figure 10 EM Pump Mounted for Test Sections

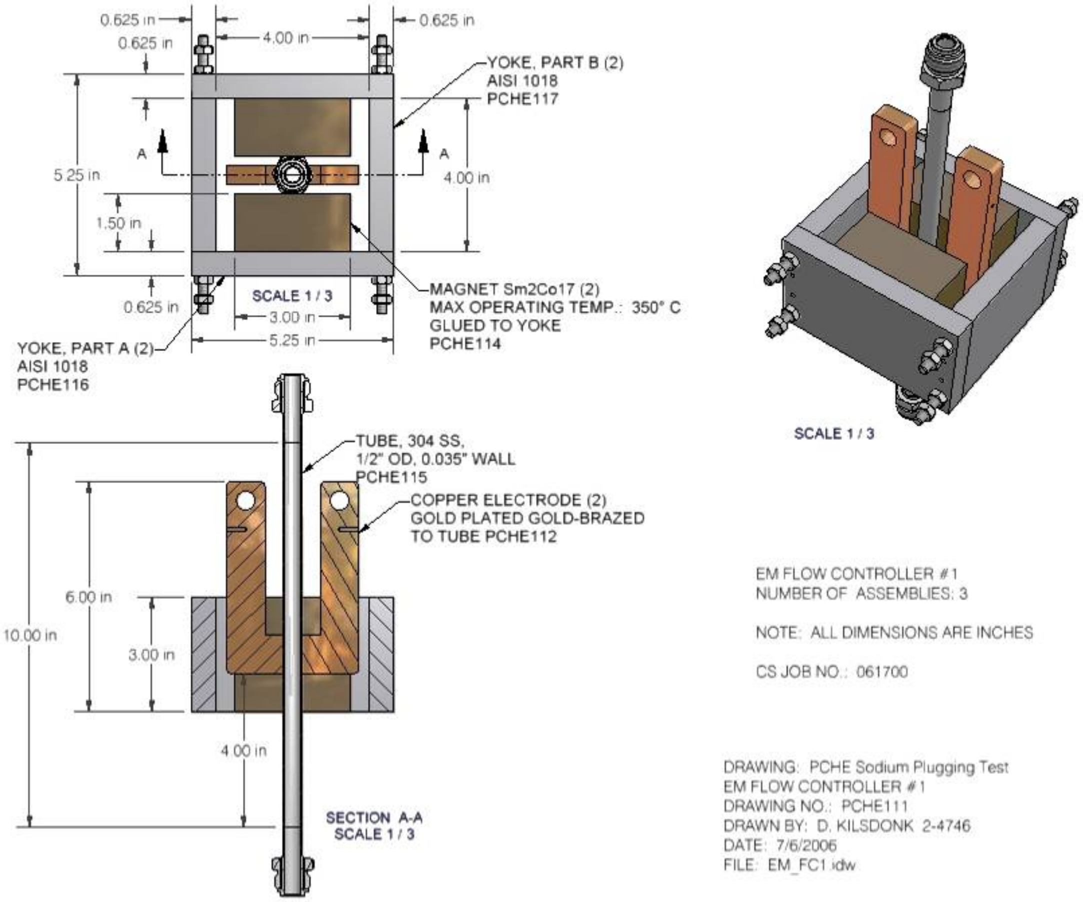

Figure 11 EM Flow Controller Design

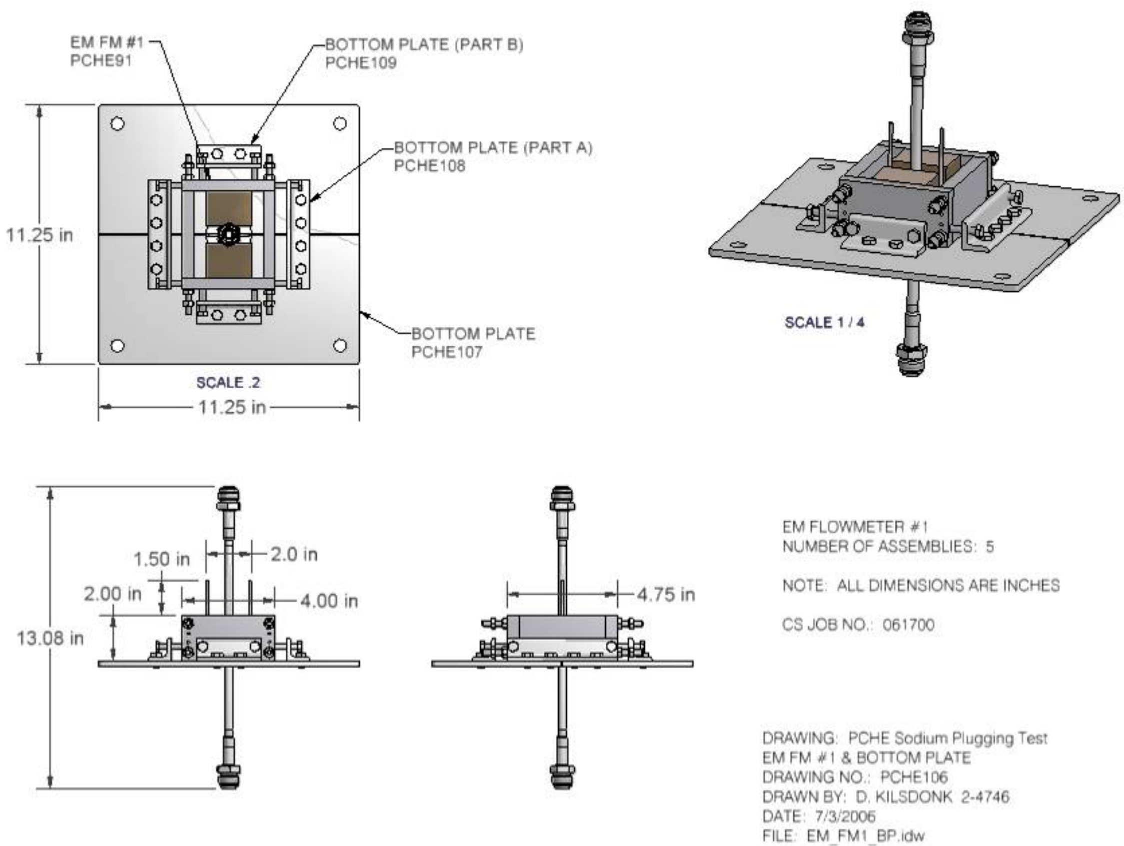

Figure 12 EM Flow Controller Mounted for Test Section

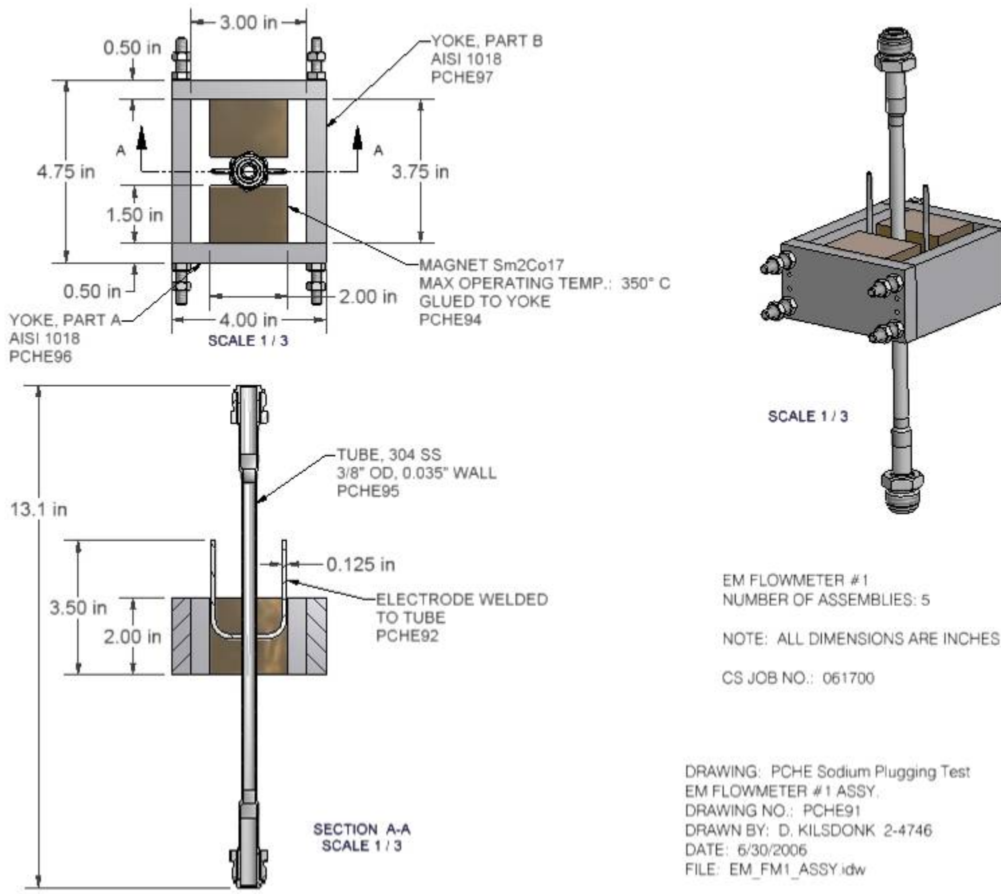

Figure 13 EM Flow Meter Design

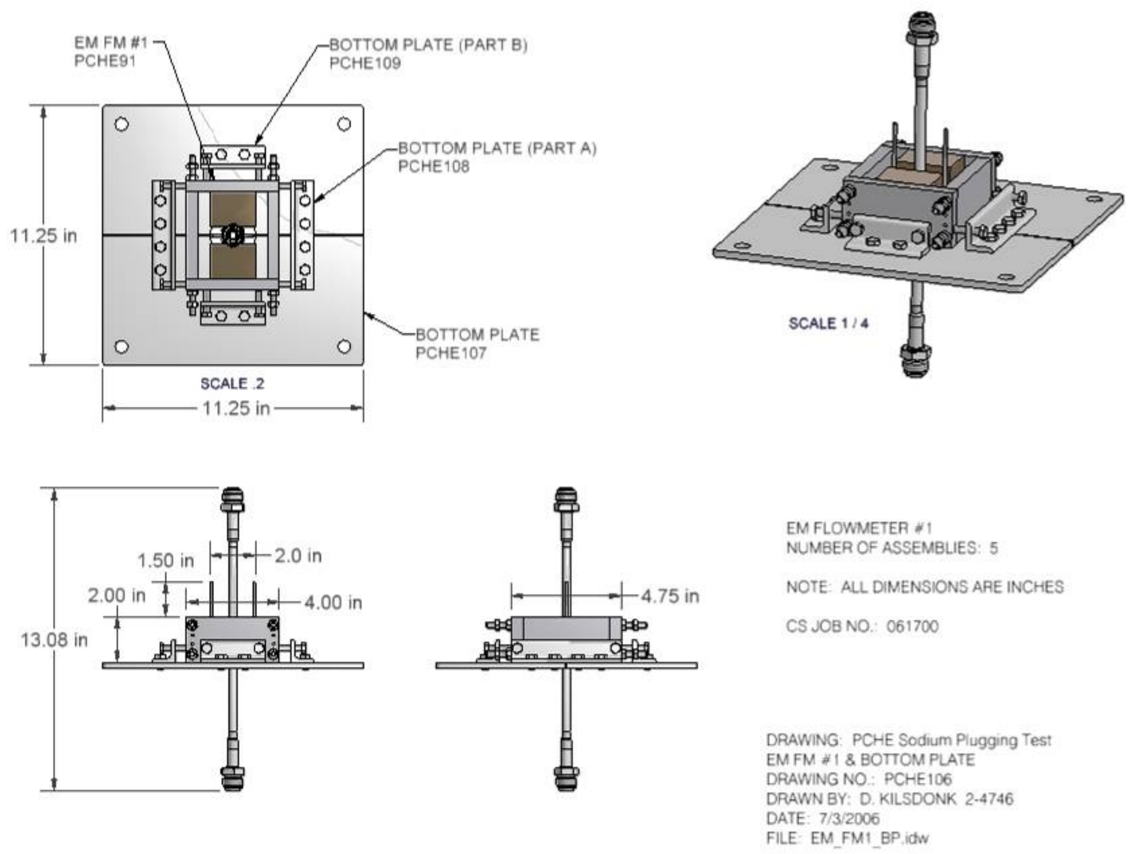

Figure 14 EM Flow Meter Mounted in the Loop System

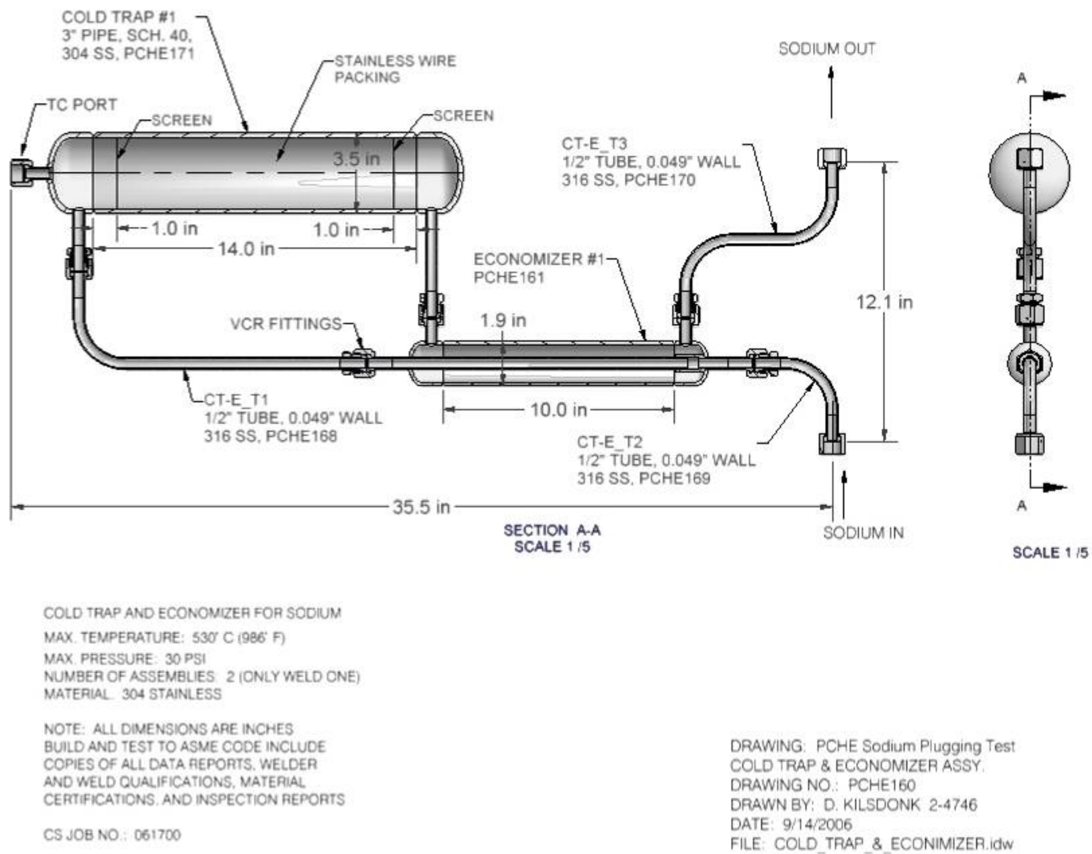

Figure 15 Cold Trap/Economizer Assembly

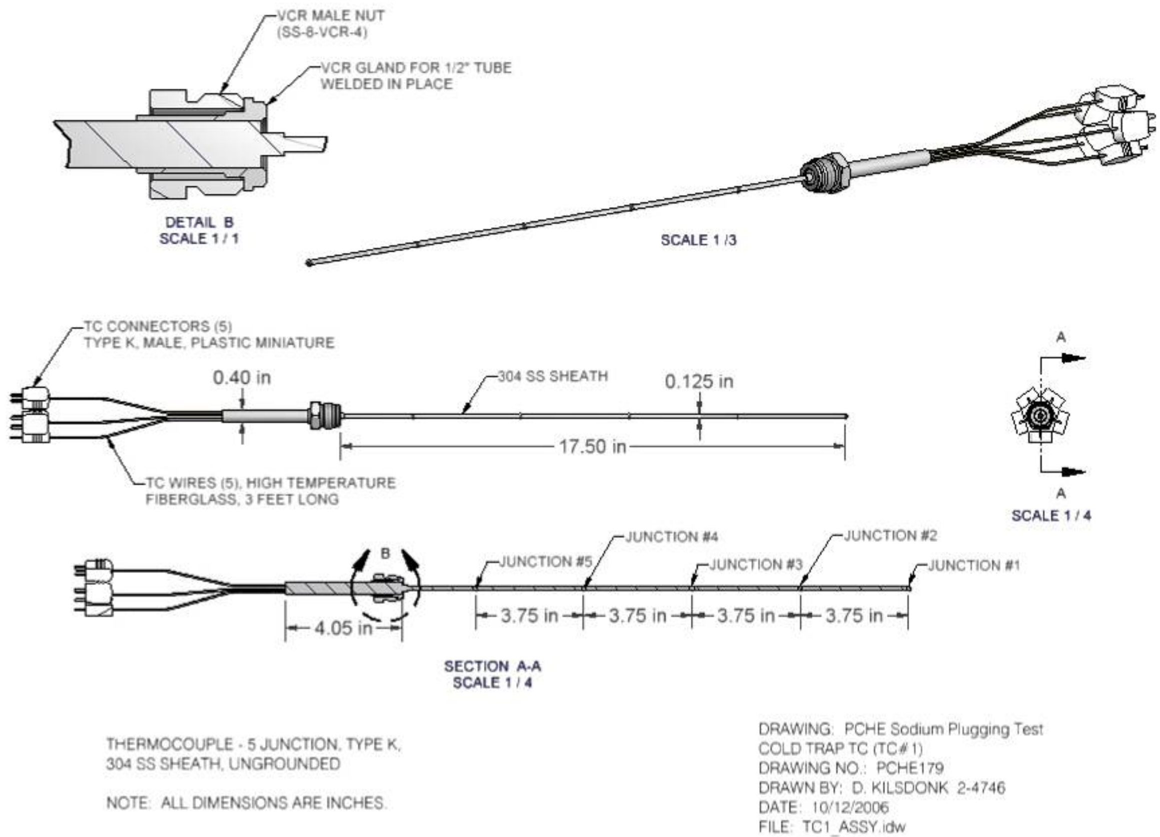

Figure 16 Cold Trap Thermocouple Probe

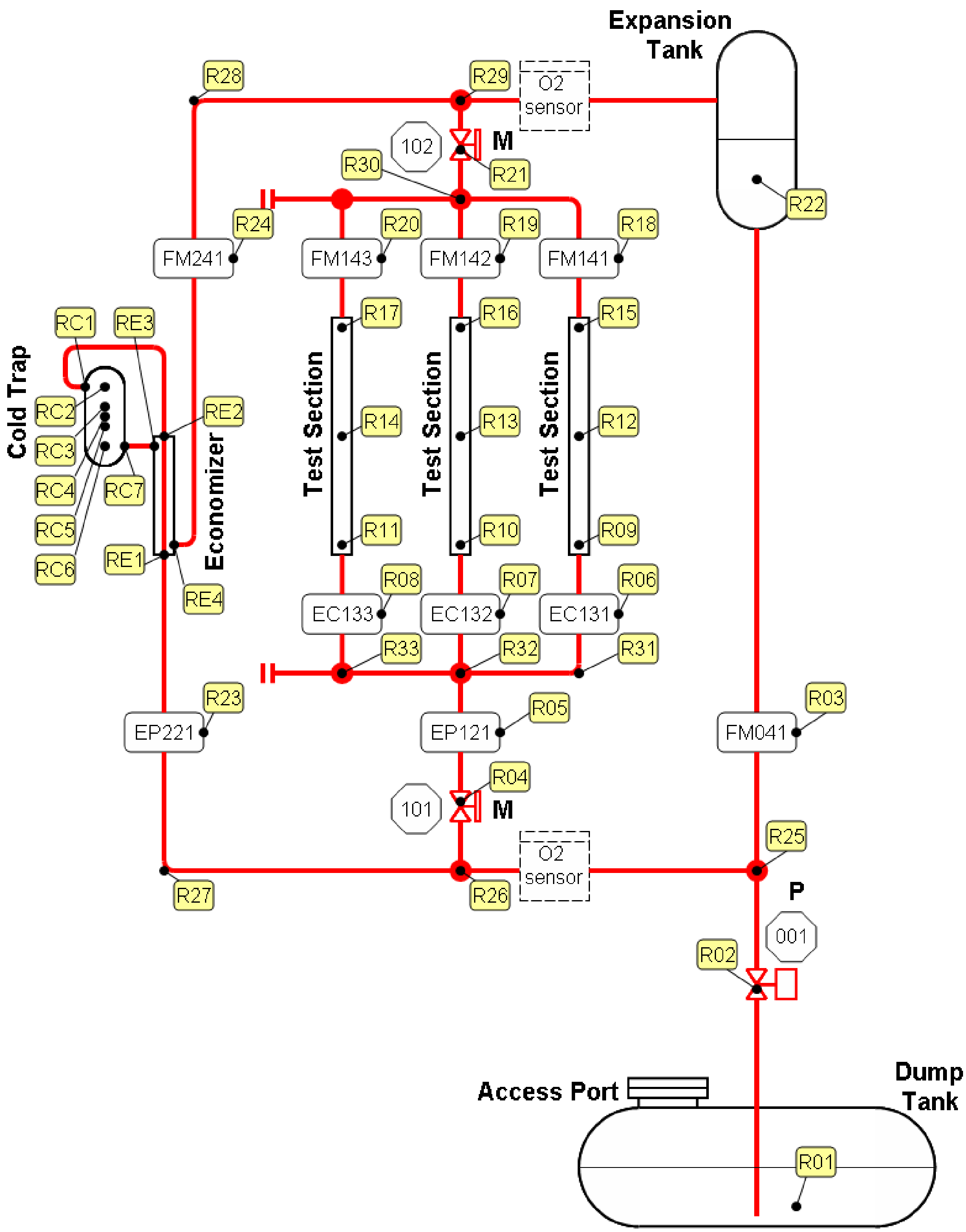

Figure 17 Recording Thermocouple Locations.

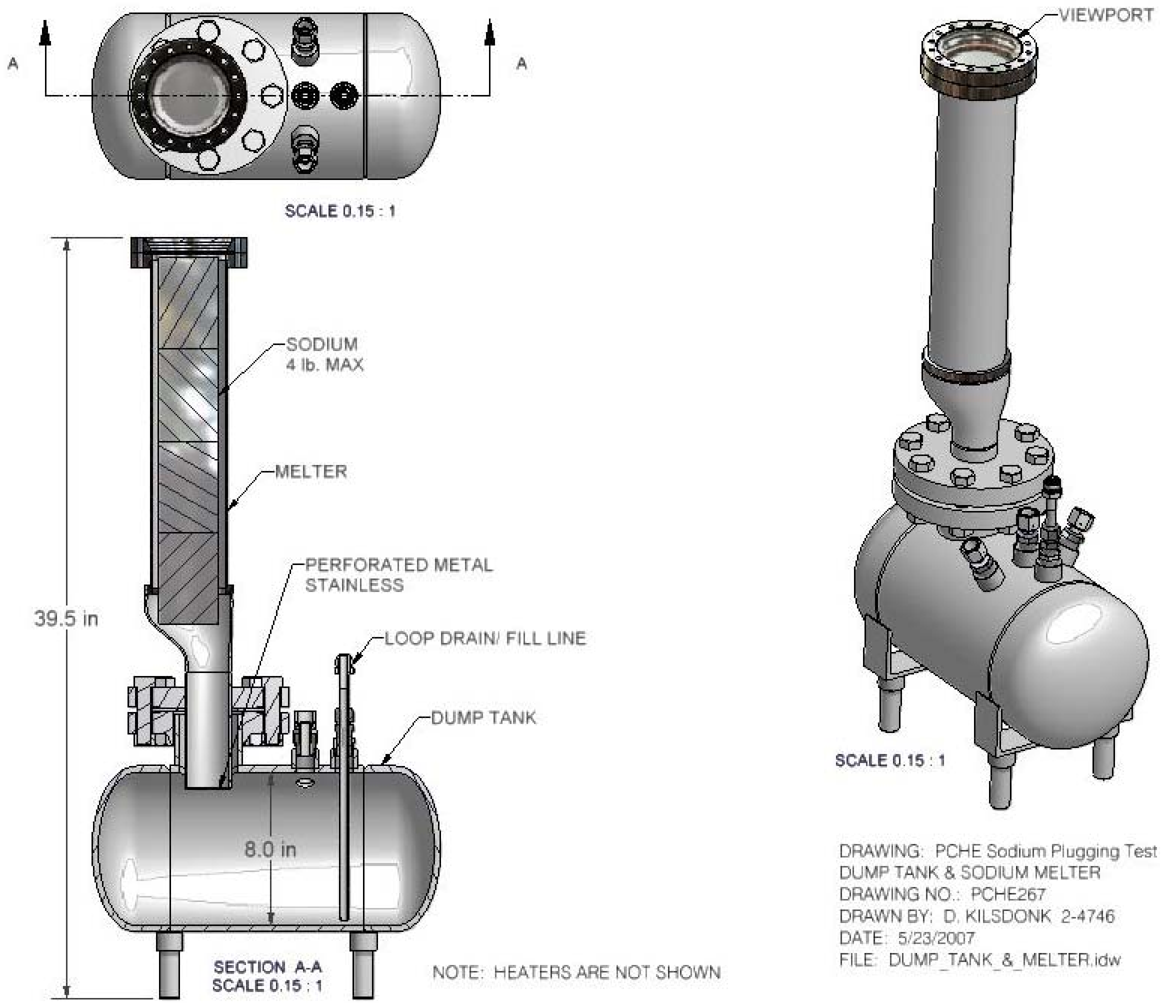

Figure 18 Sodium Melter Attached to Dump Tank

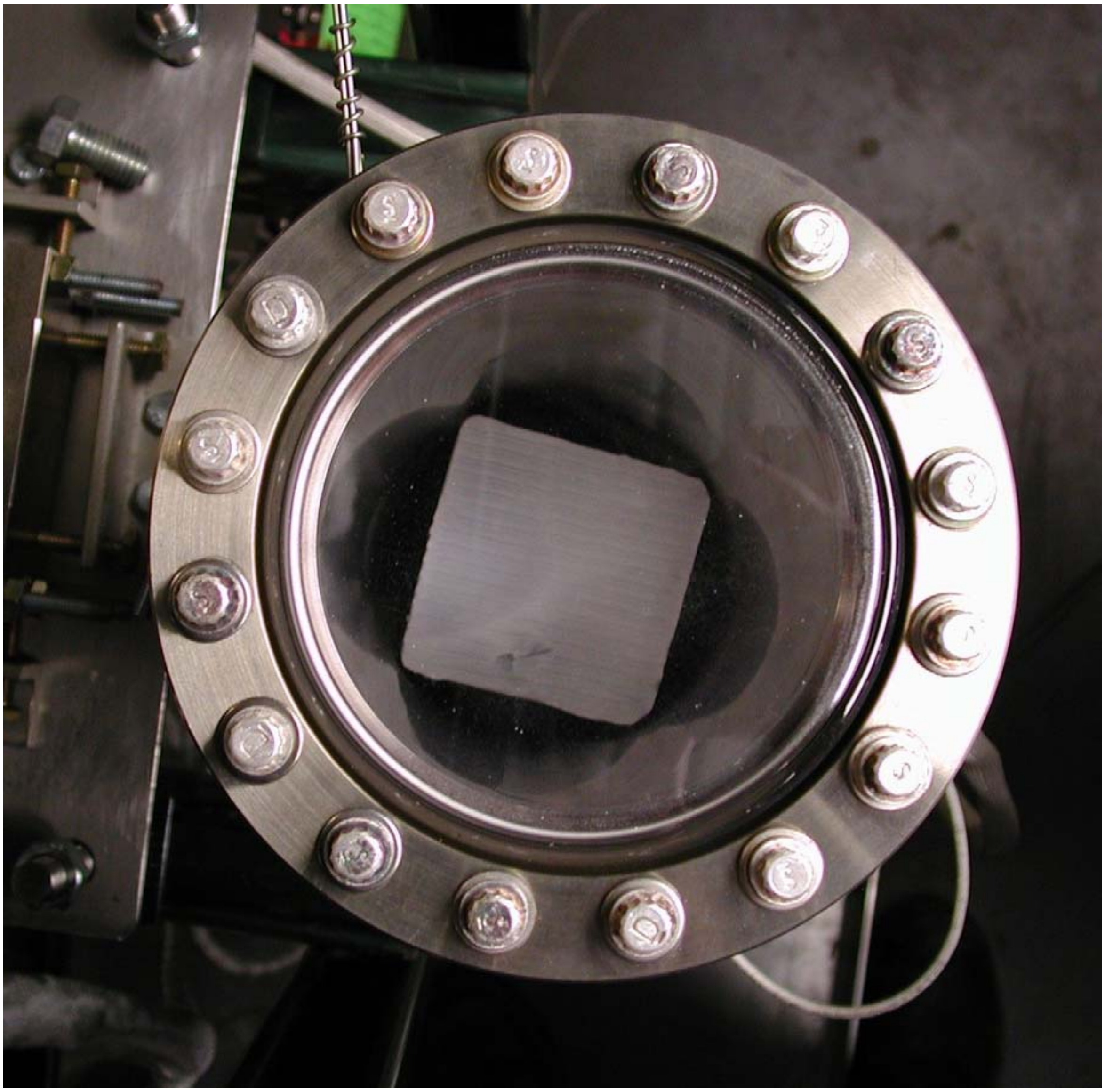

Figure 19 Sodium Slug Placed in Melter

Figure 20 Inside of Melter After Sodium Melting and Draining

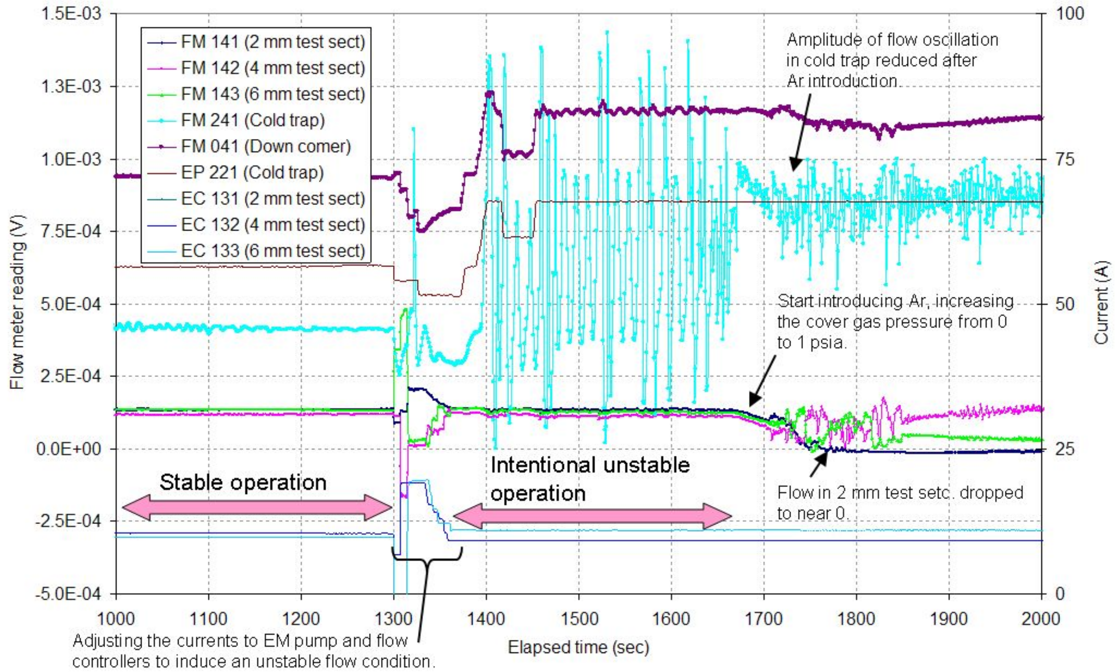

Figure 21 Operation Under Vacuum; Effect of Introduction of Argon Gas (1/2 - 1 psia)

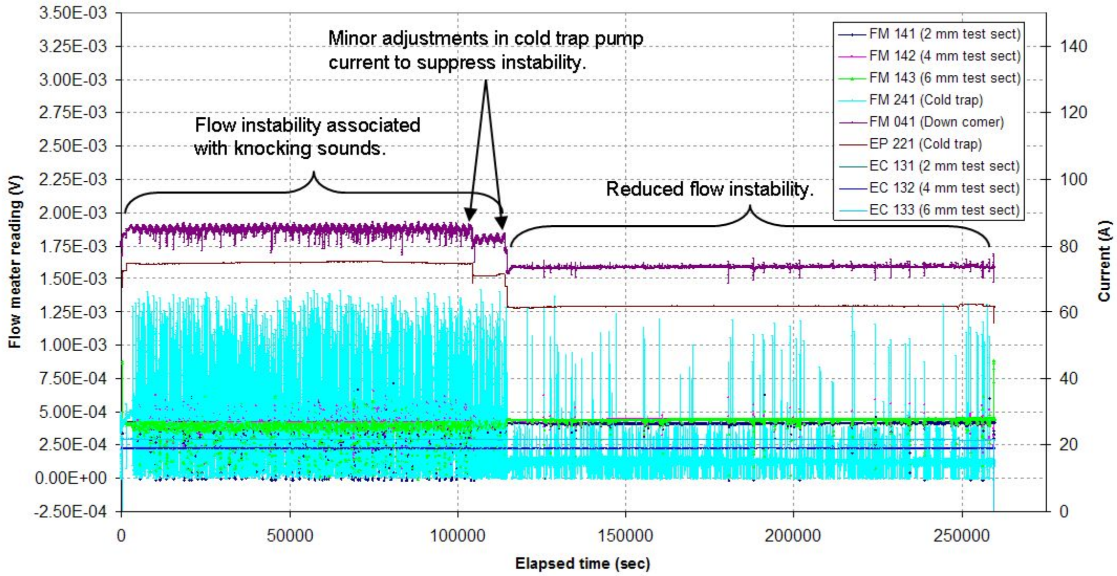

Figure 22 Operation Under Vacuum; 3-day Run

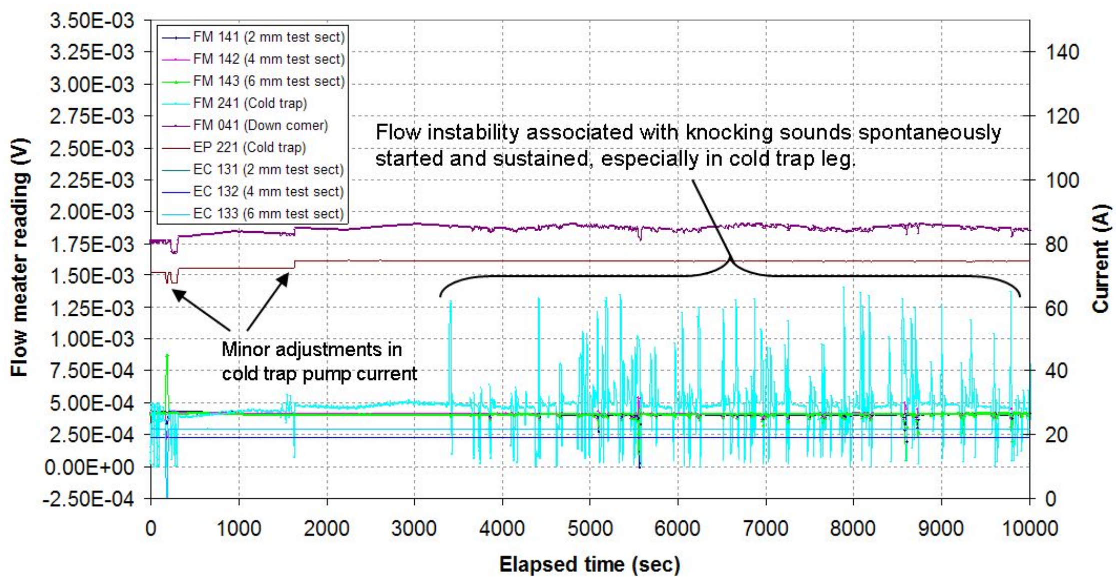

Figure 23 Operation Under Vacuum; Spontaneous Occurrence of Flow Instability

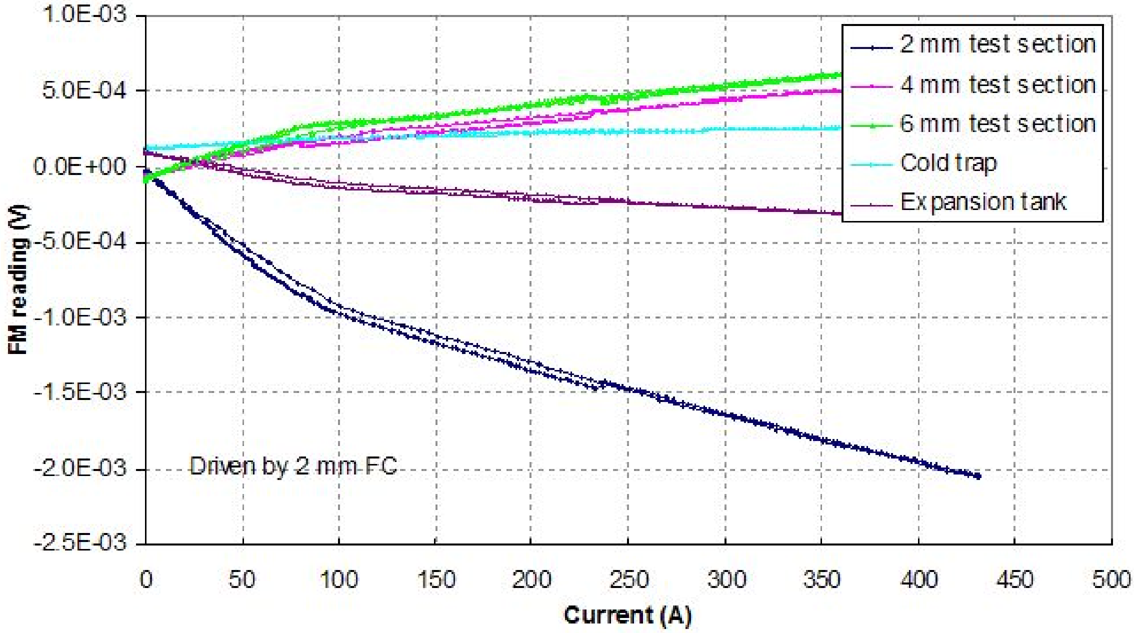

Figure 24 Operation Under Argon Cover Gas (1 psig); Flows Driven by 2-mm Test Section Flow Controller at Loop Temperature of 300°C

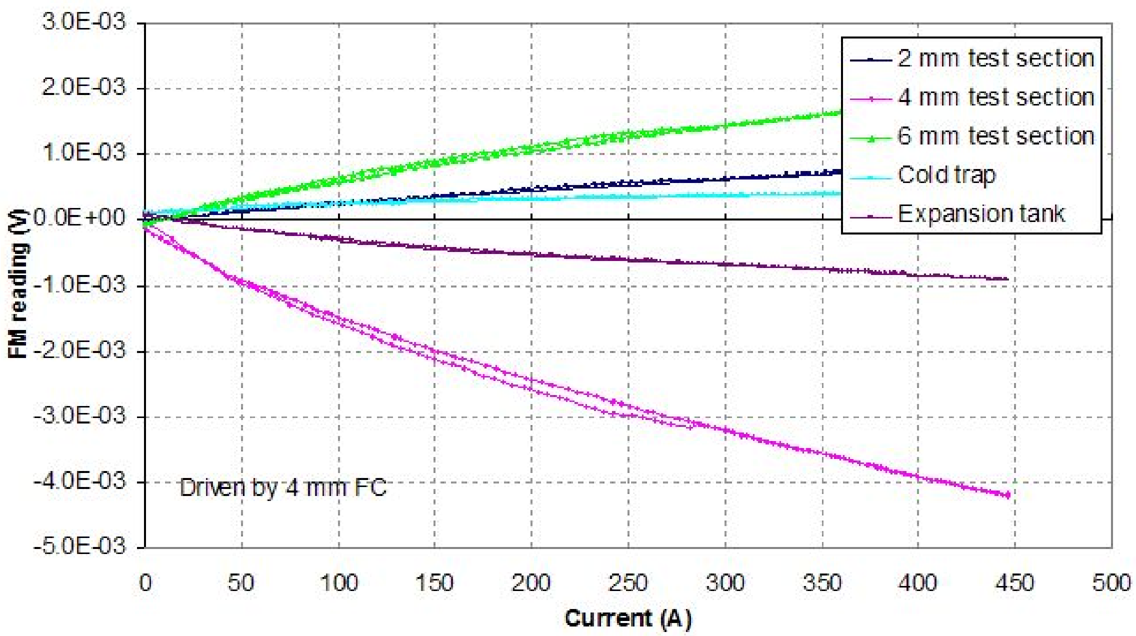

Figure 25 Operation Under Argon Cover Gas (1 psig); Flows Driven by 4-mm Test Section Flow Controller at Loop Temperature of 300°C

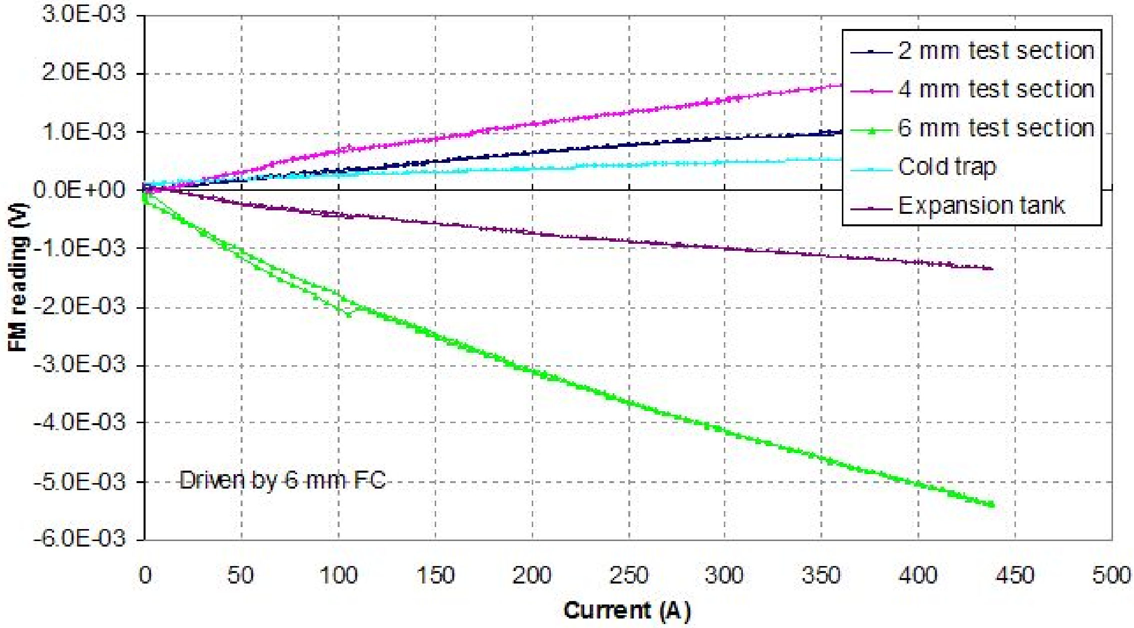

Figure 26 Operation Under ArgonCover Gas (1 psig); Flows Driven by 6-mm Test Section Flow Controller at Loop Temperature of 300°C

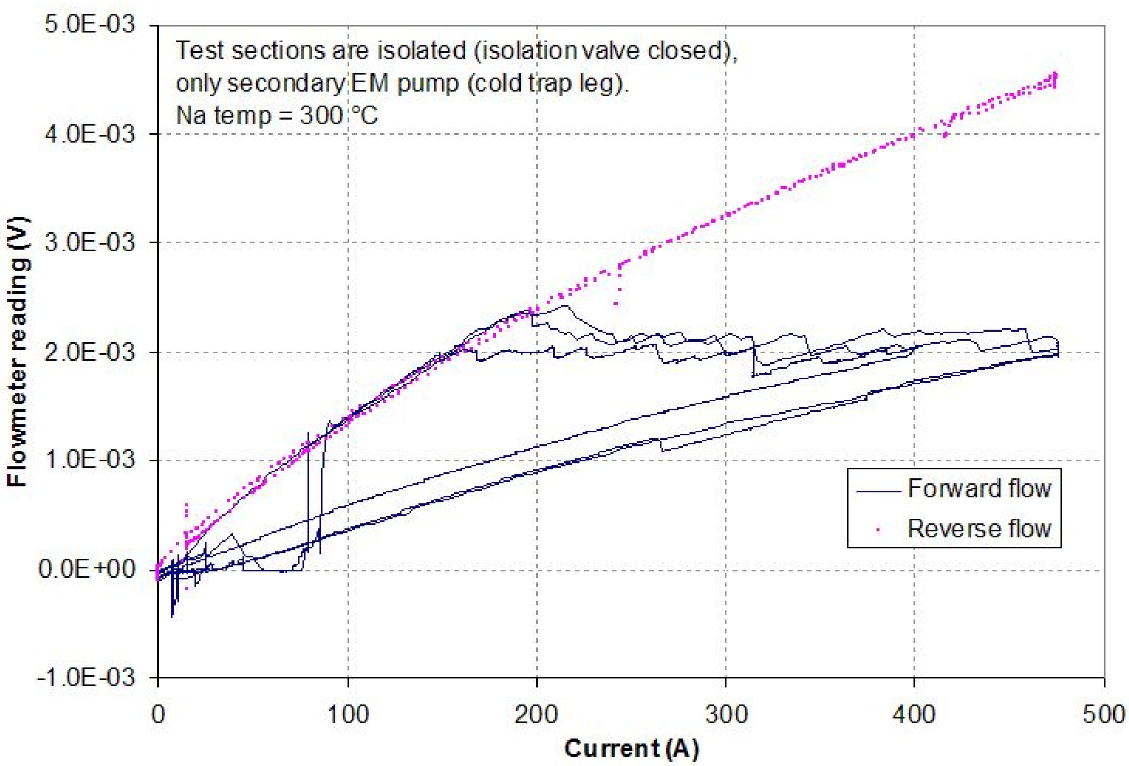

Figure 27 Operation Under Argon Cover Gas (1 psig); Flows Driven by Cold Trap Pump at Loop Temperature of 300°C

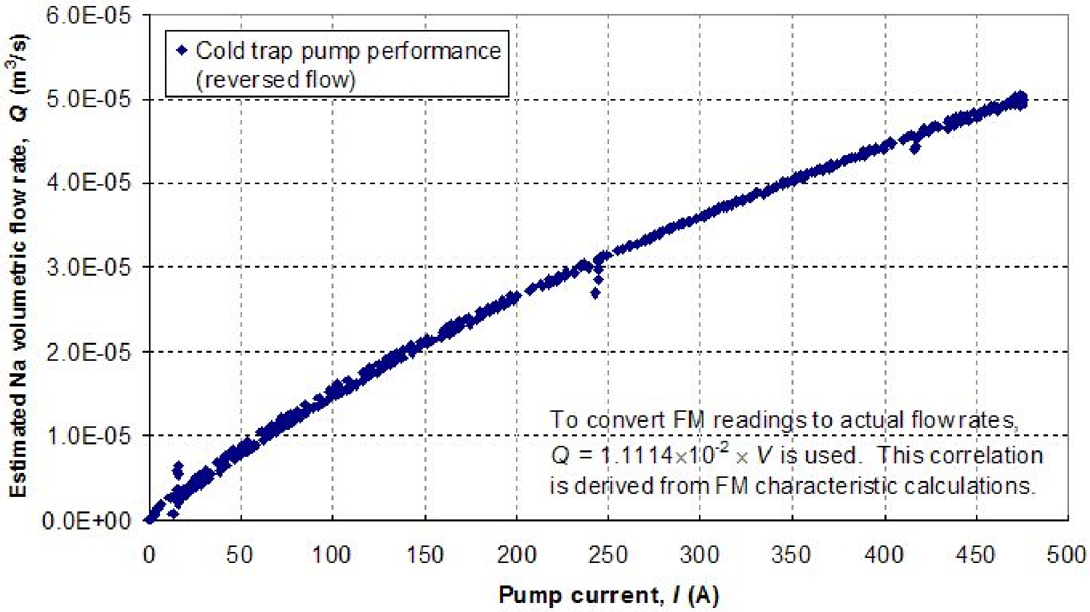

Figure 28 Operation Under Argon Cover Gas (1psig); Cold Trap Pump Performance (Reverse Flow) at Loop Temperature of 300°C

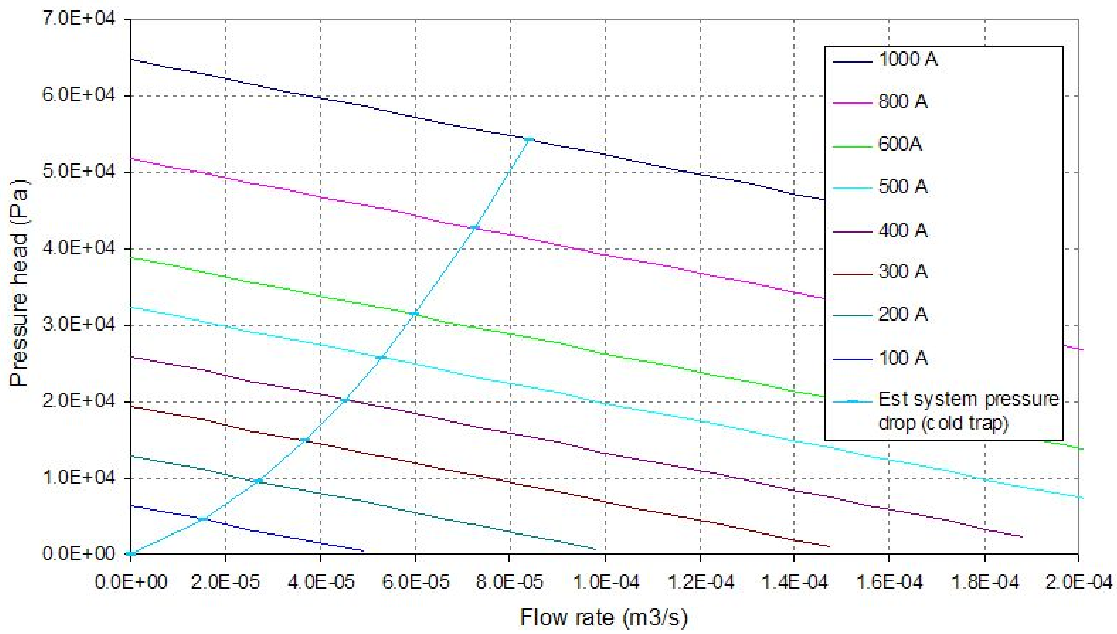

Figure 29 Operation Under Argon Cover Gas (1 psig); Estimates of Cold Trap Flow Pressure Drop at Loop Temperature of 300°C

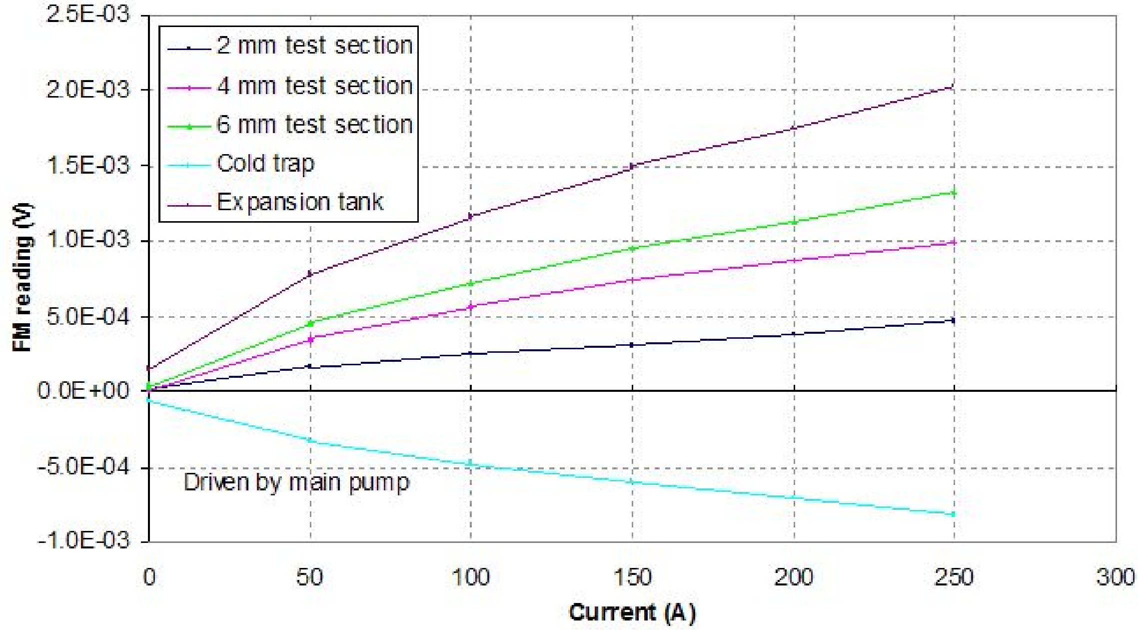

Figure 30 Operation Under Argon Cover Gas (1 psig); Flows Driven by Main Pump at Loop Temperature of 300°C

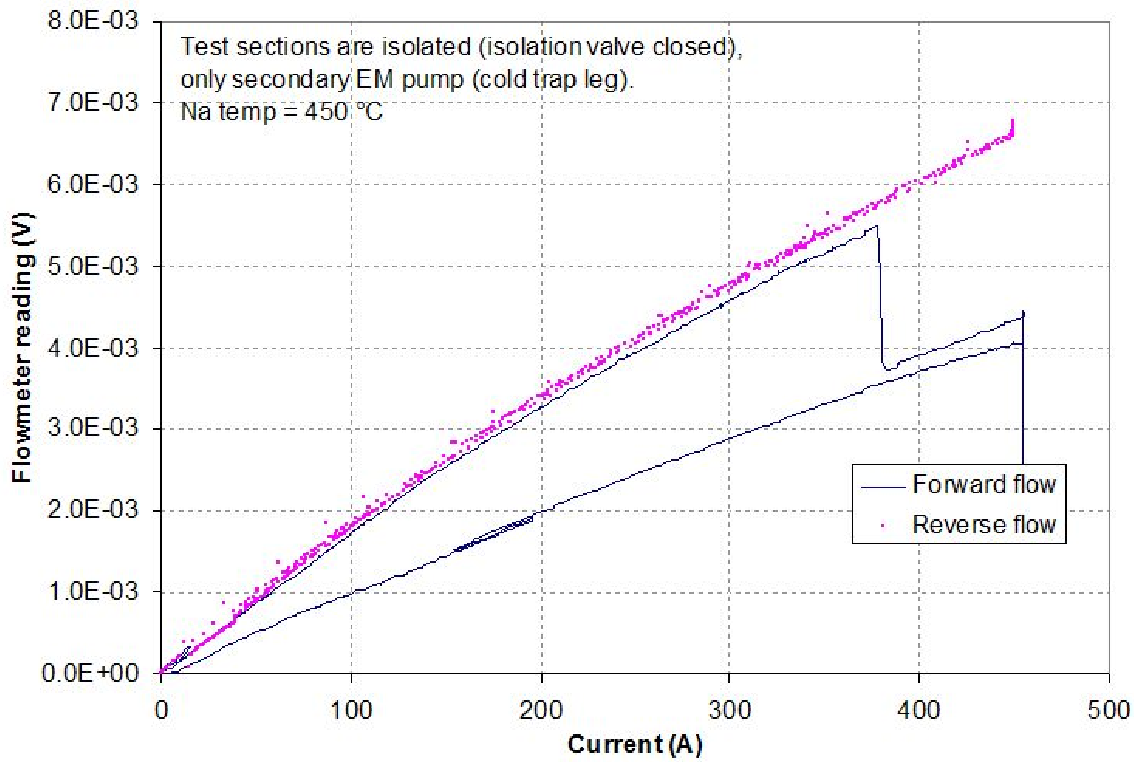

Figure 31 Operation Under Argon Cover Gas (1 psig); Flows Driven by Cold Trap Pump at Loop Temperature of 450°C

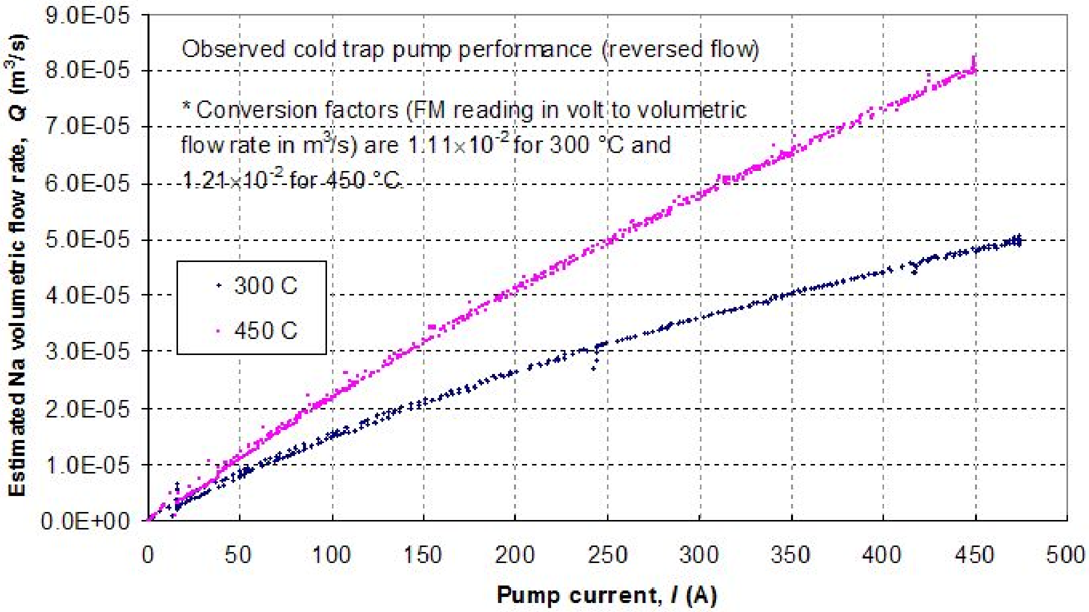

Figure 32 Operation Under Argon Cover Gas (1 psig); Comparison of Cold Trap Pump Perfomances (Reverse Flow) at Loop Temperatures of 300°C and 450°C